The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0332-1649.htm

SPECIAL ISSUE PAPER

Electrical machines and power-electronic systems for high-power wind energy generation applications

Part I – market penetration, current technology and advanced machine systems

Z.Q. Zhu and Jiabing Hu
Department of Electronic and Electrical Engineering,
The University of Sheffield, Sheffield, UK

Abstract

Purpose – Wind energy has matured to a level of development at which it is ready to become a generally accepted power generation technology. The aim of this paper is to provide a brief review of the state of the art in the area of electrical machines and power-electronic systems for high-power wind energy generation applications. As the first part of this paper, latest market penetration, current technology and advanced electrical machines are addressed.

Design/methodology/approach – After a short description of the latest market penetration of wind turbines with various topologies globally by the end of 2010 is provided, current wind power technology, including a variety of fixed- and variable-speed (in particular with doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) supplied with partial- and full-power converters, respectively) wind power generation systems, and modern grid codes, is presented. Finally, four advanced electrical-machine systems, viz., brushless DFIG, open winding PMSG, dual/multi 3-phase stator-winding PMSG and magnetic-gear outer-rotor PMSG, are identified with their respective merits and challenges for future high-power wind energy applications.

Findings – For the time being, the gear-drive DFIG-based wind turbine is significantly dominating the markets despite its defect caused by mechanical gears, slip rings and brush sets. Meanwhile, direct-drive synchronous generator, especially utilizing permanent magnets on its rotor, supplied with a full-capacity power converter has become a more effective solution, particularly in high-power offshore wind farm applications.

Originality/value – This first part of the paper reviews the latest market penetration of wind turbines with a variety of mature topologies, by summarizing their advantages and disadvantages. Four advanced electrical-machine systems are selected and identified by distinguishing their respective merits and challenges for future high-power wind energy applications.

Keywords Doubly fed induction generator (DFIG), Market penetration,
Permanent magnet synchronous generator (PMSG), Power generations, Wind turbines, Wind power,
Electric power generation

Paper type General review

COMPEL: The International Journal
for Computation and Mathematics in
Electrical and Electronic Engineering
Vol. 32 No. 1, 2013
pp. 7-33
© Emerald Group Publishing Limited
0332-1649
DOI 10.1108/03321641311293731

1. Introduction

Wind power is considered as the most promising renewable energy and has been under extensive development globally. It is reported that in the past five years the average growth rates of globally annual- and cumulative-installed capacities are 36.1 and 27.3 percent, respectively, (BTM Consult Aps – A Part of Navigant Consulting, 2011). More than 35 GW of new wind power capacity was installed around the world in 2010 in spite of global recession and economic crisis, bringing the total installed capacity up to 194.4 GW worldwide by the end of 2010. As a result, wind energy has become a generally accepted power generation technology and the penetration of wind power in the world's electricity supply has reached 1.92 percent and it is forecasted to be 8.4 percent by 2019 (GWEC, 2011).

Meanwhile, wind power technology has also undergone a dramatic transformation in the last decade, with proven technology for turbines, electrical machines as well as power-electronic systems. Variable-pitch control and variable-speed operation are well developed for turbines and generators, respectively, to improve the efficiency and reliability of the power generation systems. As a consequence, numerous variable-speed pitch-controlled wind turbines are installed in modern wind farms. At present, most installed wind turbine generators are in the power range of 1.5-5 MW, and the gear-drive doubly fed induction generator (DFIG)-based wind turbines are still dominating the markets for the time being. The future trend of wind power generation systems is to continuously increase the stand-alone capacity of wind turbines and generators so as to reduce the cost of generated electricity. Numerous research efforts have been made for larger systems, targeting 5-10 MW level, especially for offshore wind farms. In these wind power generation systems, a direct-drive synchronous generator (SG) with permanent magnets (PMs) or electrically excited (EE) and a full-capacity power converter has been proven to be a more effective solution compared with the DFIG-based system, particularly for offshore applications, due to its low maintenance cost without gear boxes, complete decoupling from the grid, wider operating range and enhanced capability of fault ride through, i.e. low-voltage ride through (LVRT) capability. Further, utilizing PMs on the rotor instead of wound rotor and dc excitation becomes more attractive owing to high power density, high efficiency and no slip-ring maintenance.

One task of this paper is to briefly investigate the latest market penetration of wind turbines with various topologies globally by the end of 2009, followed by four electrical machine systems. The other attempt is focused on a comprehensive survey of power electronics and control systems for high-power wind energy applications, which will be presented in the second part.

The rest of this first part is organized as follows. Section 2 depicts the global market penetration of wind turbines by the end of 2010, with European offshore wind power and world's top 10 turbine manufacturers highlighted. In Section 3, the present wind power technology is surveyed, including respective comparisons of fixed- and variable-speed wind turbines, and variable-speed concept utilizing full- and partial-power converters. Modern grid codes consisting of harmonic standards and fault ride through capability are outlined for wind farms. Section 4 reviews four novel electrical machine systems, namely, brushless DFIG, open winding permanent magnet synchronous generator (PMSG), dual stator winding PM machine and magnetic-geared outer-rotor PMSG for future high-power wind generation applications, with their merits and challenges outlined. Finally, some conclusions are drawn in Section 5.

2. Market penetration of wind turbines by the end of 2010

This section depicts the global status of wind power penetration according to the annual reports by BTM Consult ApS (BTM Consult Aps – A Part of Navigant Consulting, 2011) and Global Wind Energy Council (GWEC, 2011) published in the early 2011.

2.1 Global wind power market

Figure 1(a) and (b) shows the 2010s top 10 countries in newly- and cumulative-installed wind power capacities, respectively. As shown, more than 35.9 GW of new wind power capacity was installed around the world in 2010 and nearly half of these additions were made in China, which took the place of the USA to lead the global turbine market in both annual- and cumulative-installed capacities. Other Asian areas, like the OECD Pacific, the region increased its cumulative capacity from 42,037 MW in 2009 to 63,645 MW in 2010, a growth of 51.4 percent. It worth pointing out that the US market dropped dramatically compared to 2009, with only 5,115 MW of new capacity added, which was around half of its installation in 2009. Europe lost its previous position as the largest wind power continent, although 27.9 percent of all new installation in 2010 were added in Europe, as will be presented in the following sub-section.

For the purpose of further illustration, Figure 2 shows the annual- and cumulative-installed wind power capacities worldwide from 1996 to 2010. It is worth noting that both annual and cumulative wind power capacities installed across the whole world increased almost at different exponential rates. Despite the decrease in annual installations, i.e. down from 38.6 GW in 2009 to 35.9 GW in 2010, global installed capacity was increased by 22.5 percent during the year and stands at 194.4 GW at present.

2.2 European wind power market and offshore wind power

Figure 3 shows the cumulative-installed wind power capacities for different European countries, i.e. Germany, Spain, Italy, France and the UK, from 2002 to 2010. As seen from Figures 1 and 3, Germany continues to lead Europe, adding 1,493 MW in 2010 for a total capacity of 27,214 MW, while Spain led the European league tables for newly installed capacity, with additions of 1,516 MW, bringing its total up to 20,676 MW.

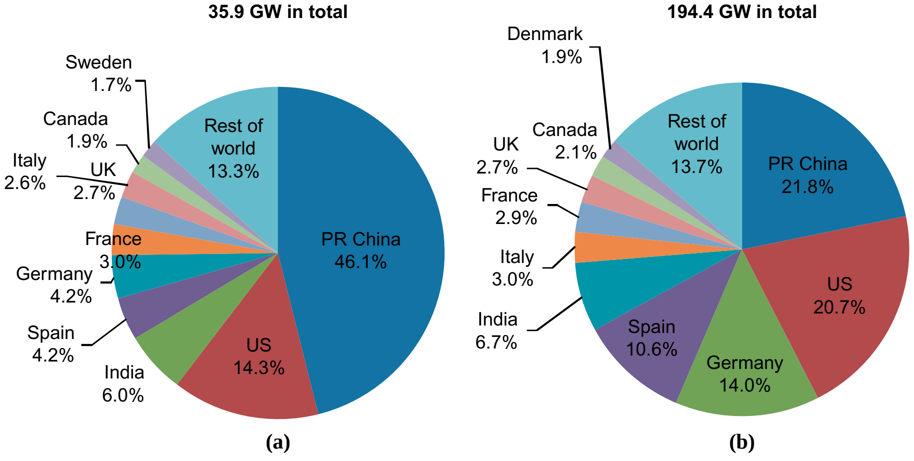


Figure 1. Top 10 countries in (a) newly- and (b) cumulative-installed capacities in 2010

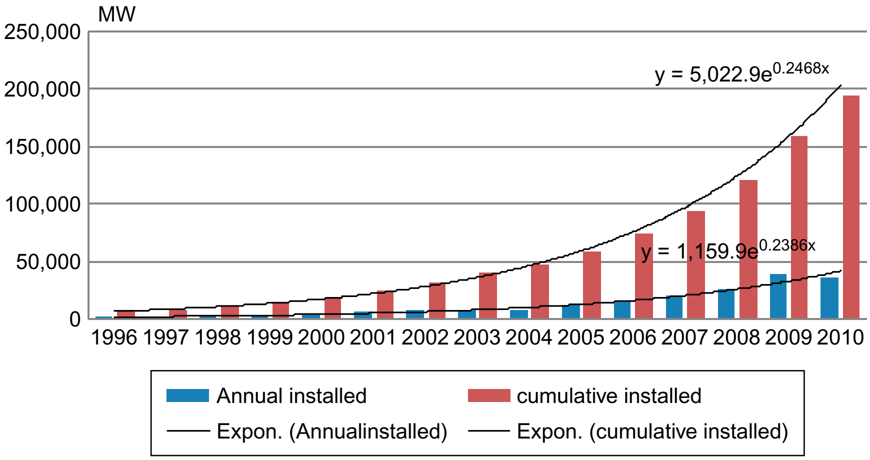


Figure 2.
Global annual- and cumulative-installed wind power capacities from 1996 to 2010

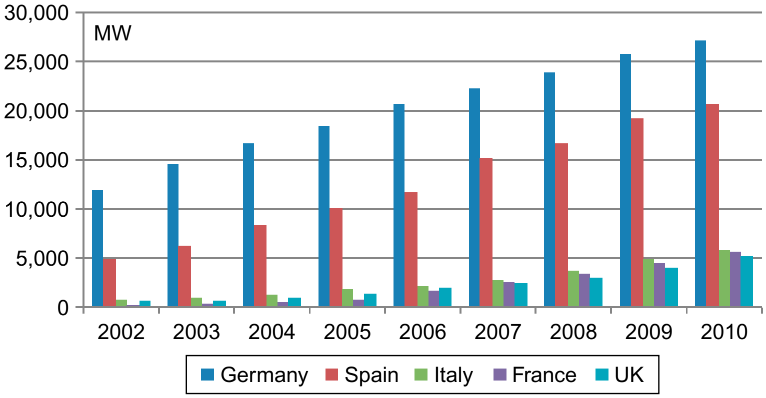


Figure 3.
Cumulative-installed wind power capacities of different European countries from 2002 to 2010

Offshore wind energy, although still in its infancy, is starting to have an increasing impact on European wind power development. The wind resources in Europe's waters make it a prime location for offshore wind development, and offshore wind power will be key to European energy future. By the end of 2010, a total of 1,138 wind turbines were installed and grid connected in European waters, bringing the total installed capacity offshore in Europe to 2,946 MW. These are spread across 39 wind farms in nine European countries. In terms of size they range from 2 MW (Lely, The Netherlands, built in 1994) to 209 MW (Horns Rev 2, Denmark, built in 2009).

The main offshore markets in Europe are the UK (1,341 MW) and Denmark (854 MW), followed by The Netherlands (247 MW), Belgium (195 MW), Sweden (164 MW), Germany (42 MW), and Ireland (25 MW). In 2010, 308 wind turbines in 18 separate offshore wind farms were installed in European waters, totaling 883 MW of new capacity – a 51 percent increase on 2009 installations. The UK continues to hold its position as the world's leading market for offshore wind energy, with 1,341 MW installed at the end of 2010, 458 MW of which came on line in 2010.

Besides, looking ahead at the offshore wind farms currently under construction, both average water depths and distance to shore are set to increase further to reach an average 25.5 m of water depth and an average distance of 35.7 km.

2.3 Wind turbine manufacturers

Figure 4(a) and (b) shows the top 10 lists of wind turbine suppliers in 2009 and 2010, respectively. As shown, the most significant change in the supply market was the strong growth of Chinese wind turbine suppliers, four of which are now among the top 10 and with strong positions. These are Sinovel (No. 2), Goldwind (No. 4), Dongfang (No. 7) and United Power (No. 10), which ranked at Nos 3, 5 and 7, respectively, in 2009.

By comparing Figure 4(a) with (b), almost all the longer established companies in the top 10 list lost significant market share in 2010. GE Wind encountered a significant drop in market share, from 12.4 percent in 2009 down to 9.6 percent. The Suzlon Group, together with Repower as a whole accounts for 6.9 percent of the world market in 2010, compared to 9.6 percent in 2009. Siemens Wind registered 5.9 percent of the market during the both years. One new name appeared in the top 10 list, which was the Chinese supplier, United Power.

As can be seen, the most significant trend in 2010s wind market was the booming Chinese wind industry. Other features of 2010 were (BTM Consult Aps – A Part of Navigant Consulting, 2011):

- Along with a modest up-scaling in turbine capacity from the supply of more multi-MW turbines for use on land, the demand for offshore wind turbines was higher than the previous year, with 1,444 MW supplied in 2010. The average turbine size delivered to the market was 1,655 kW, slightly higher than in 2009 (1.60 MW).
- In the Asian markets, smaller turbines are preferred. The average size delivered to India in 2010 was therefore 1,293 kW, whereas in China the average turbine supplied was 1,469 kW. By contrast, the average delivered to the UK market reached 2,568 kW.
- Another significant trend was the increasing supply of wind turbine concepts with a direct-drive design. This emerging technology accounted for around 17.6 percent of the world market in 2010, contributed mainly by Enercon (GER), Goldwind (CN) and Hara XEMC (CN).

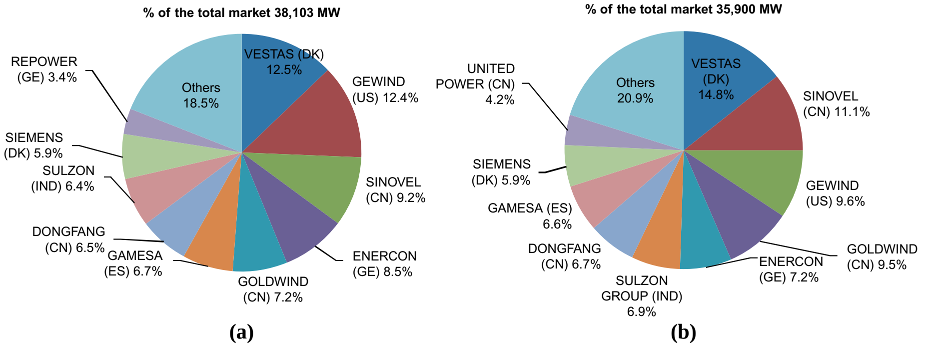


Figure 4.
Top 10 lists of turbine manufacturers in (a) 2009 and (b) 2010

On the other hand, Denmark is also a key player in terms of supplying offshore technology, and Danish manufacturers Siemens Wind Power and Vestas Wind Systems accounted for 95 percent of European new installed offshore capacity in 2010, with Vestas installing 555 MW and Siemens 278 MW in 2010, respectively. Repower (30 MW) and BARD (20 MW) are the other two main manufacturers whose offshore turbines came online in 2010. It is worth pointing out that a small floating GAIA turbine (33 kW) was also installed off the Danish coast.

3. Current wind power technology

3.1 Fixed- and variable-speed wind turbines

As indicated in Section 2, wind energy has matured to a level of development at which it is ready to become a generally accepted power generation. Meanwhile, wind turbine technology has undergone a dramatic transformation as well during last three decades, developing from a fringe science in 1980s to the modern wind turbines in 2000s by combining the latest techniques in power systems, power electronics, generators, mechanical drive train designs, and aerodynamics. Wind power is quite different from the traditional electricity generation with synchronous generators due to the remote locations of wind resources and the stochastic variations of wind. Further, owing to different integrations of wind turbines into the electrical power systems, as shown in Figure 5, there exit a variety of wind turbine designs on the market. For clear illustrations, Figure 6 shows various topologies of wind turbine generation systems available from different turbine manufacturers.

As shown in Figure 6, both induction and synchronous generators can be used for wind turbine systems. Induction generators can be used in a fixed-speed system or a variable-speed one, while synchronous generators are normally used in power electronic interfaced variable-speed systems (Figure 6(d), (f)-(h)). Three types of induction generators are mainly used in wind power conversion systems: cage rotor,

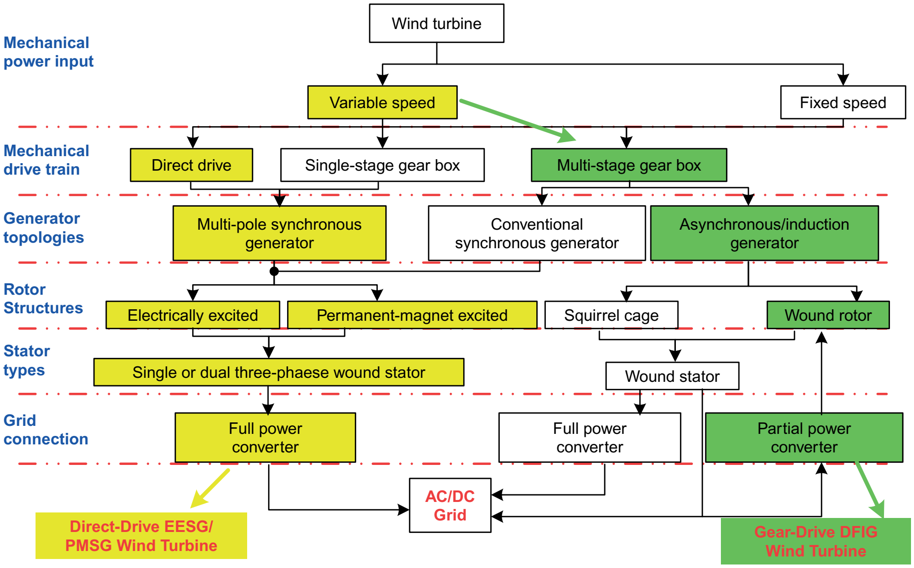


Figure 5.
Simplified roadmap for wind power generation systems

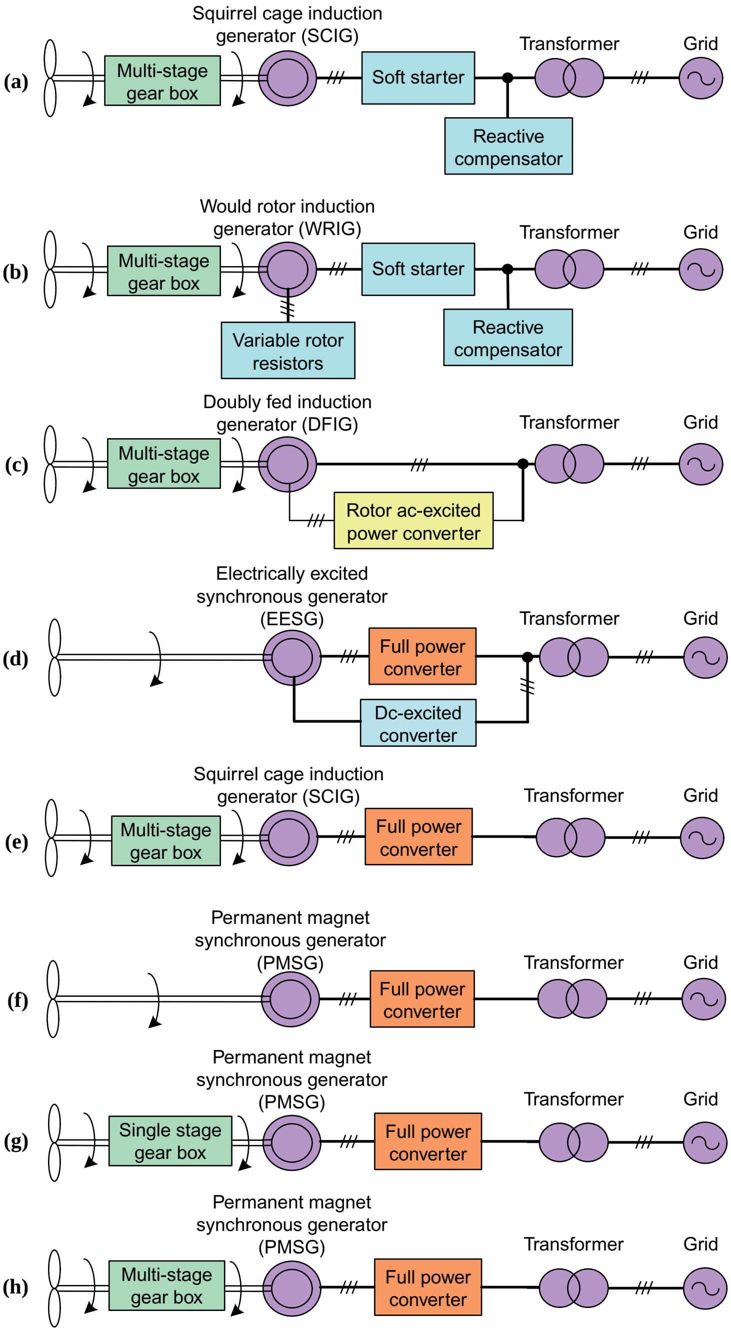


Figure 6.
Different topologies of wind power generation systems

wound rotor with slip control by changing rotor resistance, and DFIGs. The cage rotor induction machine can be directly connected into an ac system and operates at a fixed speed (Figure 6(a)) or uses a full-capacity power-electronic system to operate at variable speeds (Figure 6(e)). The wound rotor generator with rotor-resistance-slip control (Figure 6(b)) is normally connected to an ac system directly, but the slip control provides the ability of changing the operation speed in a limited range. The DFIGs provide a wider range of speed variation depending on the rating of power-electronic converter systems (Figure 6(c)).

Table I lists the applied wind turbine topologies of 2010s top 10 turbine manufacturers, including the rated power, wind turbine types corresponding to those shown in Figure 6, control features and some generator characteristics based on 2011s publicly available datum on the largest and newest wind turbines from each manufacturer (Vestas Turbine Overview, 2011; GE Wind Turbines, 2011; Sinovel SL1500/3000 Series Wind Turbines, 2011; Goldwind Turbines Overview, 2011; Enercon Wind Turbines, Product Overview, 2011; Suzlon Product Brochures, 2011; Dongfang Wind Turbines, 2011; Gamesa Wind Turbine Catalogue, 2011; Siemens Wind Turbine Brochures, 2011; China Guodian United Power – Product and Service, 2011). As shown in Figure 4(b), the ten major companies dominating the world wind turbine market at the end of 2010, totally account for almost 80 percent of the global market. As represented in Table I, the most attractive concept is the variable-speed wind turbines with pitch control, i.e. topologies shown in Figure 6(c)-(h), which indicates a clear market dominated by variable-speed concept wind turbines. Further, the most used generator type is still the induction generator (DFIG and SCIG), while three manufacturers of the top 10, namely Enercon, GE Wind and Goldwind, prefer to use the synchronous generator (EE or permanent-magnet excited, EESG or PMSG). It is worth noting that Vestas Wind Systems (V112/3 MW), Siemens Wind Power (SWT-3.0-101/3 MW) and Gamesa (G128/4.5 MW) have also launched on wind turbines with reduced-stage gear-box drive or direct drive PMSGs, respectively, for offshore wind farms.

It can be seen that four of the top 10 wind turbine suppliers have gear-drive systems with full-power converters, which employ either PMSGs (Vestas Wind Systems' V112/3 MW, Gamesa's G128/4.5 MW, GE's GE/2.5 MW), or asynchronous SCIGs (Siemens Wind Power's SWT-2.3-101/2.3 MW, SWT-2.3-93/2.3 MW, SWT-2.3-82/2.3 MW and SWT-3.6-107/3.6 MW). Table I also shows that four companies of the top 10 offer gearless direct-drive variable-speed wind turbines, namely, GE/4.0 MW, Goldwind's GOLDWIND62/1.2 MW and GOLDWIND70/1.5 MW, Enercon's E70/2.3 MW, E101/3.0 MW and E126/7.5 MW, and Siemens Wind Power's SWT-3.0-101/3 MW. This emerging technology accounted for around 14 percent of the world market in 2009, contributed significantly by Enercon (GER) and Goldwind (PRC). There is thus a clear trend towards direct-drive wind turbines, in particular for large offshore wind farms. At present the largest type of DFIG wind turbines is the gear-drive Repower/5 MW, while the Enercon's E126/7.5 MW is reported to be the largest direct-drive system.

3.2 Variable-speed concepts utilizing partial- and full-power converters

For the variable-speed concept utilizing DFIG and partial-power converters shown in Figure 6(c), the generator's rotor is excited via a converter while its stator is directly connected to the grid (Pena *et al.*, 1996; Muller *et al.*, 2002). The converter, which is capable of decoupling mechanical and electrical frequencies and making variable-speed

Table I. Applied topologies of 2010s top 10 wind turbine suppliers based on 2011s publicly available datum on the largest and newest wind turbines from each supplier

Supplier	Wind turbine	Type in Figure 6	Control and characteristics
Vestas Wind Systems (DK, 14.8%)	V90/2 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 2 MW Gen. voltage: 690 V; turbine speed range: 9.3-16.6 rpm
	V90/3 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 3 MW Gen. voltage: 1,000 V; turbine speed range: 8.6-14.8 rpm
	V112/3 MW	Figure 6(h)	Pitch and PMSG variable speed (four stages); nominal power: 3 MW Gen. voltage: 1,000 V; turbine speed range: 6.2-17.7 rpm
Sinovel Wind (PRC, 11.1%)	SL1500/1.5 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 1.5 MW Gen. voltage: 690 V; turbine speed range: N/A rpm
	SL3000/3.0 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 3.0 MW Gen. voltage: 690 V; turbine speed range: N/A rpm
GE Wind (US, 9.6%)	1.5 MW XLE	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 1.5 MW Gen. voltage: 690 V; turbine speed range: 10.1-18.7 rpm
	2.5 MW	Figure 6(h)	Pitch and PMSG variable speed (three stages); nominal power: 2.5 MW Gen. voltage: 690 V; turbine speed range: N/A rpm
	4.0 MW	Figure 6(f)	Pitch and PMSG variable speed (direct drive); nominal power: 4.0 MW Gen. voltage: 690 V; turbine speed range: N/A rpm
Goldwind (PRC, 9.5%)	GOLDWIND62/1.2 MW	Figure 6(f)	Pitch and PMSG variable speed (direct drive); nominal power: 1.2 MW Gen. voltage: N/A V; turbine speed range: 11-20 rpm
	GOLDWIND70/1.5 MW	Figure 6(f)	Pitch and PMSG variable speed (direct drive); nominal power: 1.5 MW Gen. voltage: N/A V; turbine speed range: 9-19 rpm
Enercon (GER, 7.2%)	E70/2.3 MW	Figure 6(d)	Pitch and EESG (direct drive); nominal power: 2.3 MW Gen. voltage: N/A V; turbine speed range: 6-21.5 rpm
	E101/3.0 MW	Figure 6(d)	Pitch and EESG (direct drive); nominal power: 3 MW Gen. voltage: 440 V; turbine speed range: 4-14.5 rpm
	E126/7.5 MW	Figure 6(d)	Pitch and EESG (direct drive); nominal power: 7.5 MW Gen. voltage: 440 V; turbine speed range: 5-11.7 rpm
Suzlon Group (India, 6.9%)	S88/2.1 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 2.1 MW Gen. voltage: 690 V; turbine speed range: 15-17.6 rpm

(*continued*)

Table I.

Supplier	Wind turbine	Type in Figure 6	Control and characteristics
	MM82/2 MW MM92/ MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 2.0 MW Gen. voltage: 690 V (50 Hz)/575 V (60 Hz); turbine speed range: 8.5-17.1 rpm
	MM114/3.2 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 3.2 MW Gen. voltage: 950 V (50 Hz); turbine speed range: N/A rpm
	MM104/3.4 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 3.4 MW Gen. voltage: 950 V (50 Hz); turbine speed range: 7.1-13.8 rpm
	Repower 5 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 5 MW Gen. voltage: 950 V (50 Hz); turbine speed range: 7.7-12.1 rpm
Dongfang (PRC, 6.7%)	1.5 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 1.5 MW Gen. voltage: 690 V; turbine speed range: N/A rpm
Gamesa (Spain, 6.6%)	G90/2.0 MW	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 2.0 MW Gen. voltage: 690 V; turbine speed range: 9.0-19.0 rpm
	G128/4.5 MW	Figure 6(g)	Pitch and PMSG variable speed (two stages); nominal power: 4.5 MW Gen. voltage: 660 V; turbine speed range: N/A rpm
Siemens Wind Power (DK, 5.9%)	SWT-2.3-(101, 93, 82)/ 2.3 MW	Figure 6(e)	Pitch and SCIG variable speed (three stages); nominal power: 2.3 MW Gen. voltage: 690 V; turbine speed range: 6-16 rpm
	SWT-3.0-101/3 MW	Figure 6(f)	Pitch and PMSG variable speed (direct drive); nominal power: 3.0 MW Gen. voltage: N/A V; turbine speed range: N/A rpm
	SWT-3.6-107/3.6 MW (offshore)	Figure 6(e)	Pitch and SCIG variable speed (three stages); nominal power: 3.6 MW Gen. voltage:690 V; turbine speed range: 5-13 rpm
United Power (PRC, 4.2%)	UP1500-77/82/86	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 1.5 MW Gen. voltage: 690 V; turbine speed range: N/A rpm
	UP3000-100	Figure 6(c)	Pitch and DFIG variable speed (three stages); nominal power: 3.0 MW Gen. voltage: 690 V; turbine speed range: N/A rpm

Note: "N/A" indicates the data is not available for the time being operation possible, varies the rotor-winding's electrical frequency and maintains the stator frequency constant. The wind turbine cannot operate in the full speed range from zero to the rated speed, but the speed range is determined by the converter's rating and quite sufficient within 0.7 and 1.3 pu normally. This limited speed range is caused by the fact that the converter can be considerably smaller than the rated power of the generator. Due to the fact that the converter is smaller, the losses are also lower. The control capability of the reactive power is similar to that in the full-power converter wind turbine system. For clear illustrations, the advantages and disadvantages of the DFIG-based wind power generation system can be found in Table II.

As shown in Figure 6(d)-(h), for variable-speed concept with full-power converters, the generator is completely decoupled from the grid. The energy from the generator is rectified to a dc link and after is converted to suitable ac energy for the grid integration. The majority of these wind turbines are equipped with a gear-drive multi-pole synchronous generator (Vestas Wind Systems' V112/3 MW, Gamesa's G128/4.5 MW, GE/2.5 MW), although it is quite possible (but rather rare) to use an induction generator and a gearbox (Siemens Wind Power's SWT-2.3-101/2.3 MW, SWT-2.3-93/2.3 MW, SWT-2.3-82/2.3 MW and SWT-3.6-107/3.6 MW). There are several benefits of removing the gearbox: reduced losses, lower costs due to the elimination of this expensive component, and increased reliability due to the elimination of rotating mechanical components. GE/4.0 MW, Goldwind's GOLDWIND62/1.2 MW and GOLDWIND70/1.5 MW, Enercon's E70/2.3 MW, E101/3.0 MW and E126/7.5 MW, and Siemens Wind Power's SWT-3.0-101/3 MW belong to such technology.

For comparison, the advantages and disadvantages of each wind turbine generator type for variable-speed constant-frequency operation, shown in Figure 6(c)-(h) are outlined in Table II, respectively.

Apart from the various types of generators, the power converters connecting these wind turbine generators into grid have a variety of topologies as well, and their associated control methods differ a lot, which will be discussed in detail in the second part of this paper.

3.3 Modern grid codes

Variable-speed wind turbines feature easy maximum-power-point-tracking (MPPT) operation, higher annual energy capture, independent regulation of active/reactive powers, less mechanical stress and less sensitive to flicker. But, a new problem arose with variable-speed wind turbines, particularly having full-capacity power converters. Modern forced-commutated converters used in variable-speed wind generators produce not only harmonics but also interharmonics, namely, harmonics that are not a multiple of the fundamental frequency of grid. Recently, high-frequency harmonics and interharmonics are treated in the IEC 61000-4-7 (IEC Standard 61000-4-7, 1997) and IEC 61000-3-6 (IEC Standard 61000-3-6, 1996). The methods for summing harmonics and interharmonics in the IEC 61000-3-6 are applicable to wind turbines. If the switching frequency of the inverter is not constant, the harmonics will also vary. As a result, since the switching frequency is arbitrary, the harmonics are also arbitrary. Therefore, modulation techniques with constant switching frequency, such as sinusoidal pulse-width-modulation (SPWM) and space-vector (SV) PWM, are preferred in the power converters, especially in grid-side converters of wind turbine generation systems.

On the other hand, as the wind capacity increases (shown in Figures 2 and 3), network operators have to consider that in order to enable a large-scale penetration of the wind

Table II.
Advantages and disadvantages of different variable-speed turbine generators

Generator type	Advantages	Disadvantages
DFIG (Figure 6(c))	Reduced converter cost and losses with converter rated at typically 30 percent of generator rating Suitable for high-power applications including recent trends in offshore farms Allows for independent control of both active and reactive powers Allows both generator and converter to generate or absorb reactive power as required	Increased capital cost and need for periodic slip-ring maintenance More slip ring sensitivity and maintenance in offshore wind farms Is not direct drive and therefore requires a maintenance of multi-stage gearbox for connection to wind turbine Stator winding is directly connected to the grid and susceptible to grid disturbance
SCIG (Figure 6(e))	Known as rugged machines that have very simple design, and thus lower capital cost for construction of the generator Higher availability especially for large-scale grid connected designs Relatively less sensitive to grid faults Allow for independent control of both active and reactive powers	Increased converter cost and losses since converter must be rated at the full or even more system power Generator requires reactive power and therefore increases cost of machine-side converter for initial AC-DC power conversion Is not direct drive and therefore requires maintenance of intensive gearbox for connection to wind turbine
EESG (Figure 6(d))	Applied direct drive reducing cost without gearbox required and minimum mechanical wear due to slow machine rotation Allow for independent control of both active and reactive powers Self-excited machines do not require reactive power injection from machine-side converter Possibly less generator cost compared with PMSG owing to no PMs used	Additional DC-excited converter for magnetization and increased losses accordingly Increased capital cost and need for periodic brushes maintenance For direct-drive applications, the generator's diameter is much larger than PMSG
PMSG (Figure 6(f)-(h))	Flexibility in design allows for smaller and lighter designs, and gearless topology removes cost and maintenance of drive train system and increase reliability Higher output level may be achieved due to smaller pole pitch allowed compared with EESG Eliminates the need for separate excitation and no significant losses generated in the rotor Fit for high-power offshore wind farms	Higher initial cost due to high price of PMs used, which may restrict production of such generator for larger scale grid connected turbine designs High temperatures and severe overloading and short circuit conditions can demagnetize PMs without recovery Larger generator diameter due to multi-pole design versus DFIG and SCIG

energy without compromising the power system stability, the turbines should stay connected and contribute to the grid in case of a disturbance such as a voltage dip. Wind farms should generate like conventional power plants, supplying active and reactive powers for frequency and voltage recovery, immediately after the fault occurs.

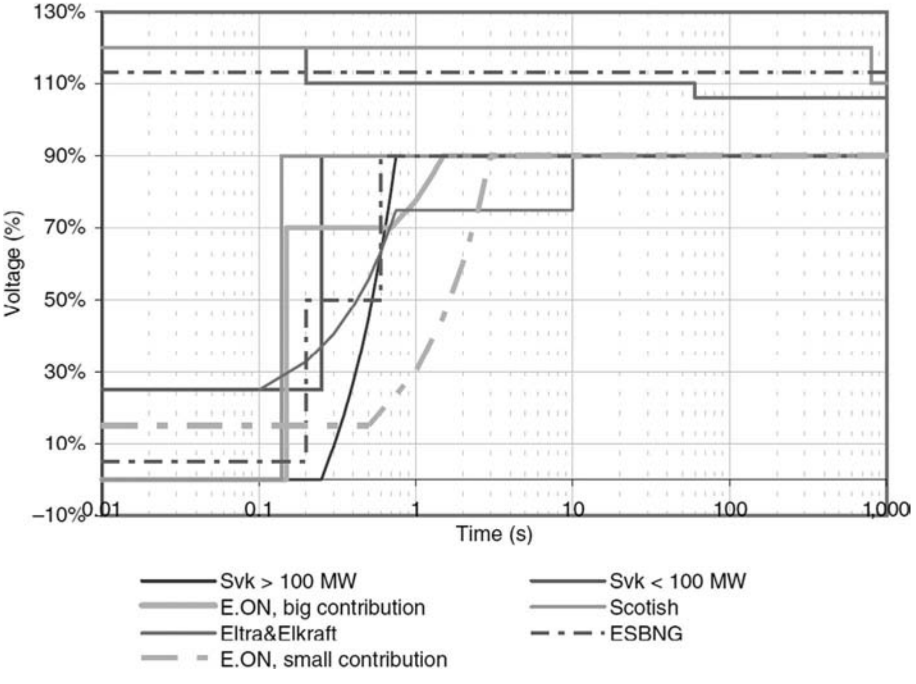
Thus, several utilities, such as Spain, Denmark, and part of Northern Germany, have introduced modern grid connection codes for wind-farm developers, covering reactive power control, frequency response, and fault ride through particularly in places where wind turbines provide for a significant part of the total power. They define the operational boundary of a wind turbine connected to the network in terms of frequency range, voltage tolerance, power factor, and fault ride through operation (Jauch *et al.*, 2005).

Among all these requirements, fault ride through is regarded as the main challenge to the grid-connected wind turbines. As shown in Figure 7 (Jauch *et al.*, 2005), the German Transmission and Distribution Utility (E.ON) regulation is likely to set the standard (Erhich *et al.*, 2006). Taking E.ON big contribution as an example, it stipulates that a wind turbine should remain stable and connected during the fault while voltage at the point of connection drops to zero of the nominal value for a period of 150 ms (Figure 7). Only when the grid voltage drops below the curve, the turbine is allowed to disconnect from the grid. When the voltage is in the area above the specific curve, the turbine should also supply a reactive power to the grid in order to support the grid-voltage restoration.

4. Novel electrical machine systems for high-power wind generations

4.1 Brushless (BL) DFIG

As represented in Table II, there exist obvious drawbacks to the use of slip rings in wound-rotor DFIGs, namely, additional cost of and bulk of a machine incorporating slip rings, and the need to maintain brush-slip and to replace brushes periodically. Although the



Source: Jauch *et al.* (2005)

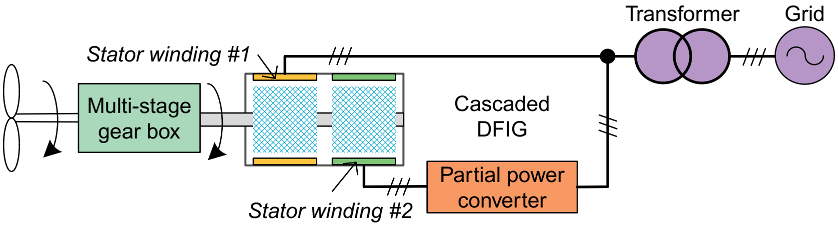
Figure 7.
Different requirements for fault ride-through capability of grid-connected wind turbines

reliability and efficiency of large wind turbines based on DFIGs have been enhanced, the faults with connecting the DFIG's rotor with power converter contribute to turbine failure rates significantly. Further, the problems with brush-slip become a troublesome issue in DFIG-based wind turbines, which will be more severe in offshore wind farms.

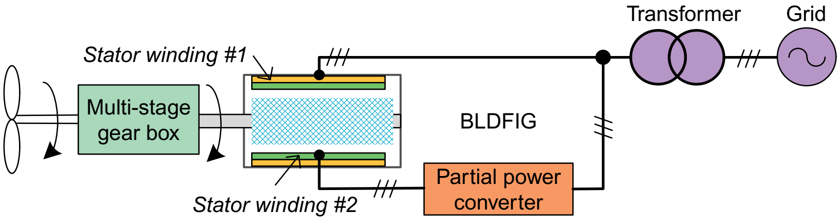
Brushless (BL) DFIG, known as a self-cascaded machine, is becoming an interesting alternative to the slip-ring DFIG owing to the complete elimination of slip rings and brushes. The stator of a BLDFIG is furnished with two separate stator windings which differ in numbers of pole pairs so as to reduce or even avoid coupling between the windings. The rotor is specially designed to couple both of the two stator windings, i.e. seven different rotor designs were investigated and compared in Roberts (2004). Generally speaking, stator winding 1 is directly connected to the power grid, and is therefore known as power winding. In contrast, stator winding 2, named the control winding, is supplied with a variable-voltage variable-frequency power converter handling a fraction of the rated power. This configuration can be shown in Figure 8. The BLDFIG can operate in several modes (McMahon *et al.*, 2006) including induction mode (with stator winding 2 open-circuited), cascade mode (with stator winding 2 short-circuited) and synchronous (doubly fed) mode. The synchronous mode is the most desirable mode for controlled variable-speed operation, especially for wind power generation applications.

The basic idea of BLDFIG can date back to 1902 (Siemens Brothers & Co. Ltd and Lydall, 1902) and has experienced three major development stages (Xu *et al.*, 2010), which can be outlined as follows:

(1) Stage 1 between 1910s and 1920s, Hunt (1914) and Creedy (1920) developed the concept of "self-cascaded induction machine", which has two wound induction motors in a special arrangement. Mechanically, the two induction machines share a common shaft, meanwhile, the two sets of rotor windings are cascaded-connected electrically. Owing to the assistance of power electronics control, this early version of brushless doubly fed induction machine with minor variations is still applied recently (Boardman *et al.*, 2001).



(a) Single-frame cascaded configuration



(b) A common stator core with two sets of stator windings

Figure 8.
Schematic of a wind-turbine driven BLDFIG system

(2) Stage 2 around 1970s, Broadway (1971, 1974) and Kusko and Somuah (1978) and others carried out further research and reported their in-depth understanding in the concept of “self-cascaded induction machine”. It was proposed to merge two sets of stator windings by a dual-tapped stator windings wound into a common stator core. Besides, it was worth noting that creative idea was Broadway’s rotor in two styles, namely, nested cage rotor and salient reluctance rotor that could be effective for the single-“self-cascaded induction machine”.

(3) Stage 3 since 1990s, the renewed interests in BLDFIG have been pushed by the rapid development in modern power electronics, which is supposed to take full advantages of possible potentials of the BLDFIGs in variable-speed drives and generation systems. Recent work on the BLDFIG includes the generalized analysis published by Williamson *et al.* (1997), studies of power flow through the machine (Gorti *et al.*, 1996) and the equivalent circuit approach proposed by Roberts (2004).

From the structure robustness point of view, the attractiveness of the BLDFIG machine is obvious, namely, the machine operates as a conventional doubly fed induction machine but eliminates all the headaches caused by brushes and slip rings, from high costs of building and maintaining the machine to the serious reliability issues. Attracted by the features of brushless and doubly fed (synchronous) operation modes, several prototype BLDFIGs were built and tested. Unfortunately, the experimental results did not show a great promise with efficiency only about 75 percent and inability to reach the designed full power (Xu and Liu, 2009).

Nevertheless, recent advances in the study of the BLDFIG allow more complete consideration on the application of this machine to variable-speed generation in wind turbines, but clearly reveal a series of fundamental issues and challenges with respects to the design and control of a BLDFIG. Compared to its counterpart DFIG with brushes and slip rings, the issues of BLDFIG to the researchers are fundamental and critical, including (Xu *et al.*, 2010):

- what are the rules for BLDFIG optimal design to maximize torque and power density;
- what are the suitable control algorithms for a BLDFIG system;
- how the energy efficiency can be substantially improved; and
- what are the ultimate limits on design and control such a machine.

Evidently, these challenges are of practical significance and application demanding. Without innovative breakthroughs to these issues, the dreamed BLDFIG technology would remain as a topic barely on academic publications.

More recently, an original design of a BLDFIG system was achieved by Xu *et al.* (2010) via finite element analysis, which is capable of 2,000 Nm in the speed range of 400-1,200 rpm with a frame size comparable to that of a conventional DFIG. It is worth pointing out that the most impressive results comprise the BLDFIG power capability more than a quarter over the designed value and energy efficiency higher than 94 percent covering 75 percent designed torque-speed regime.

4.2 Open-winding PM machines

The open-winding structure can be easily obtained by opening the star-terminal of the stator windings of the conventional machines and hence creating another set of three-phase stator terminals, as shown in Figure 9. Both terminals can be fed by two voltage source inverters (two-level and/or three-level) with single or separate dc links.

The features of this dual-inverter-fed open-winding drive system can be outlined as:

- equal power shared by both sides of each winding;
- each inverter is rated at a half machine power;
- independent control of each of the three-phase stator currents;
- double the effective PWM switching frequency across the phases;
- flexibly extended to more phases; and
- machine losses are the same as the conventional star connection.

Due to these outstanding features, open-end winding configuration has been widely applied in induction machine drives (Baiju *et al.*, 2004; Holtz and Oikonomou, 2010).

In Baiju *et al.* (2004), the open-end winding induction motor, fed by two two-level inverters with half the dc-link voltage (compared with the conventional NPC three-level scheme) from both sides, realizes a three-level inverter structure. The two inverters can be supplied by two isolated or single dc links, as shown in Figure 10(a) and (b), respectively. In the former scheme, zero-sequence currents in the phase windings can be suppressed naturally due to the use of separated dc links, while in the latter, special SVPWM technique should be employed in the two inverters to suppress the zero-sequence currents. The features of dual-inverter-fed induction machine drives shown in Figure 10 are as follows:

- Alternating common-mode voltage and zero-sequence currents can be simultaneously eliminated, even with a single dc link.
- The scheme has a simple power circuit consisting of two standard two-level inverters, and requires no neutral-point-clamped diodes. As a result, the drive does not experience any neutral point fluctuations compared to the common-mode voltage elimination scheme based on the conventional three-level NPC inverters.

Meanwhile, as presented in Holtz and Oikonomou (2010), constructing medium-voltage inverters from building blocks based on the proven three-level NPC topology is favored due to the technical and economic constraints involved with multi-level topologies of more than three-voltage levels. The circuit topology in Figure 11, consisting of medium-voltage open-end winding machines and two three-level NPC

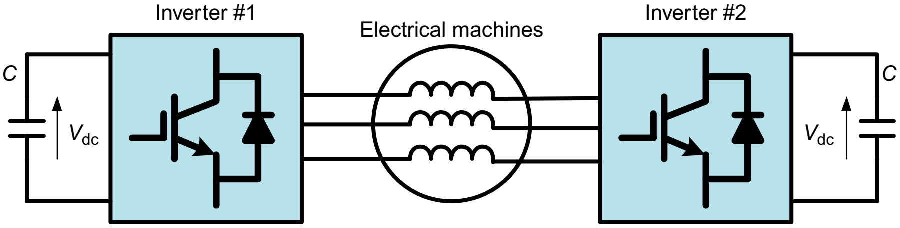
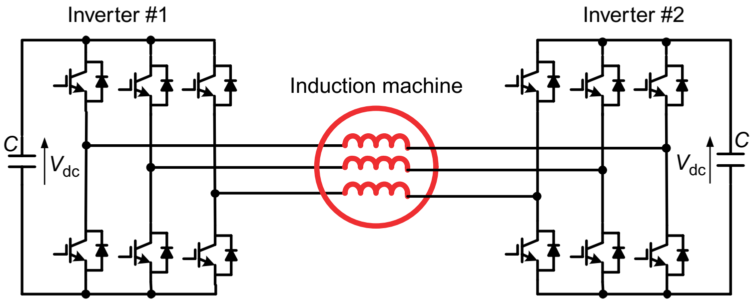
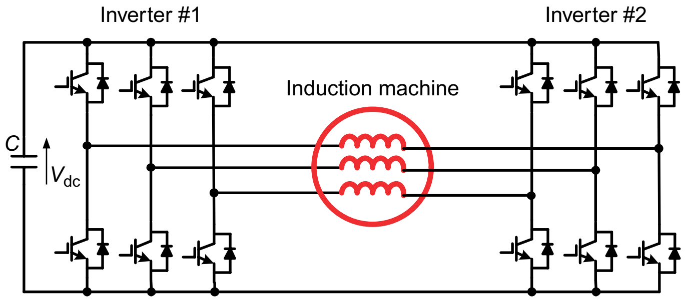


Figure 9.
Schematic of an open-winding machine fed by two individual inverters



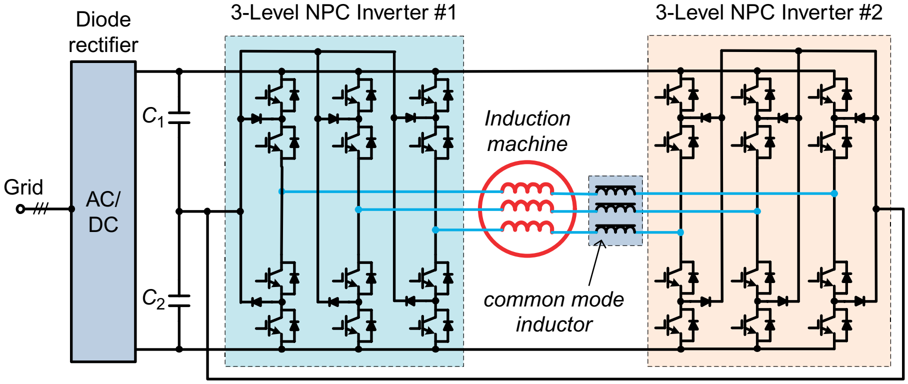
(a) With two isolated dc links



(b) With single dc link

Source: Baiju *et al*. (2004)

Figure 10. Schematic of dual-inverter-fed open-end winding induction machine drive



Source: Holtz and Oikonomou (2010)

Figure 11. Schematic of dual-NPC-inverter-fed open-end winding induction machine drive

inverters, was suggested. As shown, the two inverters are fed from the same dc link provide by diode rectifier and their output voltages add at the open phase windings of the machine, behaving as a five-level inverter. The inverters are actually series-connected. Since the machine exhibits a very low impedance for the zero-sequence components that are part of the added inverter voltages, a common-mode inductor having a high zero-sequence impedance and a low impedance for the revolving components is therefore provided in each phase to suppress the zero-sequence currents. In this case the machine can be operated at a high voltage, e.g. 8.3 kV, whereas the dc-link voltage is only 5.9 kV. Equipped with IGBT rated at 6.5 kV and 600 A, such drive systems can deliver about 5 MVA at the machine terminals. One outstanding merit is that such configuration relies on the well-proven reliable three-level inverter technology, which, in many cases, is a product of the respective manufacturers already, as shown in the Appendix.

For distributed generation applications with engine-generation systems, an open-end winding surface-mounted PM synchronous machine is used as a generator and also as series inductor for ac-dc converter (Kwak and Sul, 2008). Three stator terminals of the PM machine are connected to the inverter and the others are directly connected to the grid. As a result, the powers collected from both dc-link and the engine generator can be controlled simultaneously via only one three-phase power converter.

For a high-power (5-10 MW) medium voltage wind-turbine driven PMSG with open-end stator windings, a five-level full-power converter can be constructed by dual back-to-back connected three-level NPC converters, as shown in Figure 12. As shown, since the dc-link voltage in each BTB NPC converter is isolated, obtained and maintained from their respective grid-side converter, the common-mode inductors on the machine side can be removed. The distinct merits of this configuration are obvious, namely, lower dv/dt due to five level voltage, and easy configuration owing to well-proven commercial BTB three-level NPC converters.

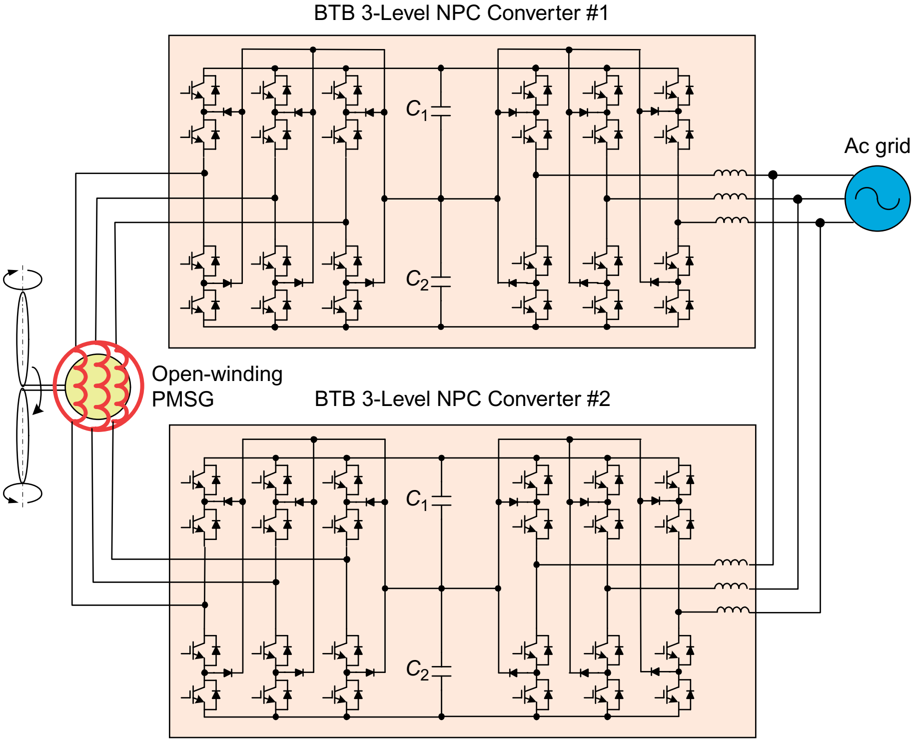


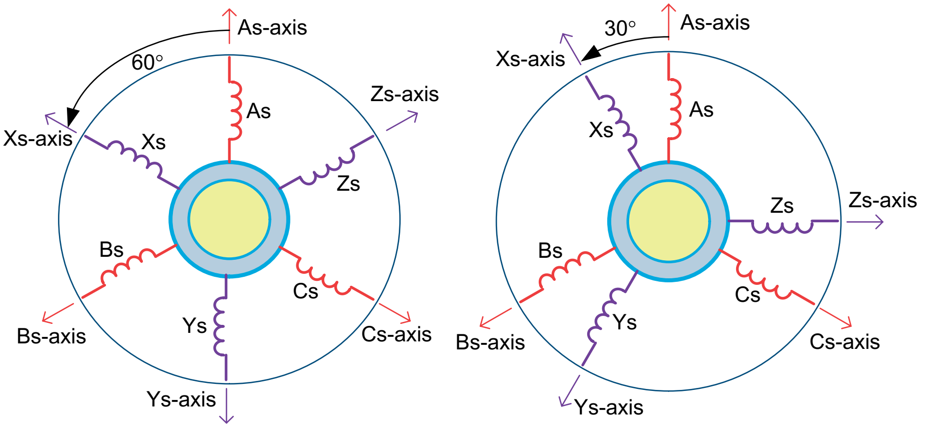
Figure 12.
Wind-turbine driven open-winding PMSG using dual back-to-back connected three-level NPC converters

4.3 Multiphase and dual/multi three-phase machines

As shown in Figure 6(c), the three-phase distribution grid has imposed the same number of phases for DFIG's stator windings, since they were directly connected to the grid via step-up transformers. While for the full-power-converter supplied wind power generation systems, as shown Figure 6(d)-(h), usually ac-dc and dc-ac converters are used to collect the wind power into the grid, it is no longer necessary to limit the phase numbers of generator's stator windings.

Potential use of multiphase (as a matter of fact, six-phase) synchronous generators was considered extensively in the 1970s and 1980s (Franklin, 1973a, b; Schiferl and Ong, 1983a, b). The perceived applications were mainly related to uninterruptible-power-supply (UPS) systems. In recent times, massive interests in the use of multiphase generators have been provoked, associated with renewable electric-energy generating sources (Vizireanu *et al.*, 2007, 2006; Brisset *et al.*, 2008; Singh *et al.*, 2006; Kato *et al.*, 2001, 2006). Permanent-magnet synchronous multiphase (in essence, nine phases) generators (Vizireanu *et al.*, 2007, 2006; Brisset *et al.*, 2008; Singh *et al.*, 2006) has become a viable solution for the direct-drive applications in wind power generation systems, while multiphase induction generators (actually with multiple three-phase windings) may have a prospect for applications in standalone self-excited generating systems in rural areas (Kato *et al.*, 2001) and low-power hydroelectric plants (Kato *et al.*, 2006).

Typically, the machine is designed with two sets of independent three-phase windings which may or may not have strong magnetic coupling. This kind of machine, as shown in Figure 13(a) and (b), is reported in literature with different names, including six-phase, split-phase, dual three-phase (DTP) or asymmetrical six-phase machine. Since the outputs of the three-phase windings are kept independent and are individually rectified, these machines are better described as "dual/multi three-phase" machines rather than as multiphase machines. The most interesting and widely discussed is the DTP machine that has two sets of stator windings spatially shifted by



(a) (b)

Notes: (a) Six-phase machine with 60 degree phase shift; (b) DTP machine with 30 degree phase shift

Figure 13. Multiphase electrical machines

30 electrical degrees with isolated neutrals, as shown in Figure 13(b). It was demonstrated by Levi (2008) that 30 electrical degrees displacement between the two stator winding sets features:

(1) elimination of the sixth-harmonic-pulsating torque component; and
(2) significant decrease of the rotor losses by reducing the rotor current harmonics in induction machines.

The potential configurations of a wind-turbine-driven DTP PMSG generation system by using two BTB two-level three-phase VSCs (one for each set of three-phase stator winding) can be shown in Figure 14(a) and (b), which are different from dc-link supplies. While for higher-power and medium-voltage PMSGs, the two-level BTB VSCs can be replaced by three-level BTB NPC-VSCs. The advantages of the dual (or more) three-phase PMSG schemes over the conventional three-phase ones are:

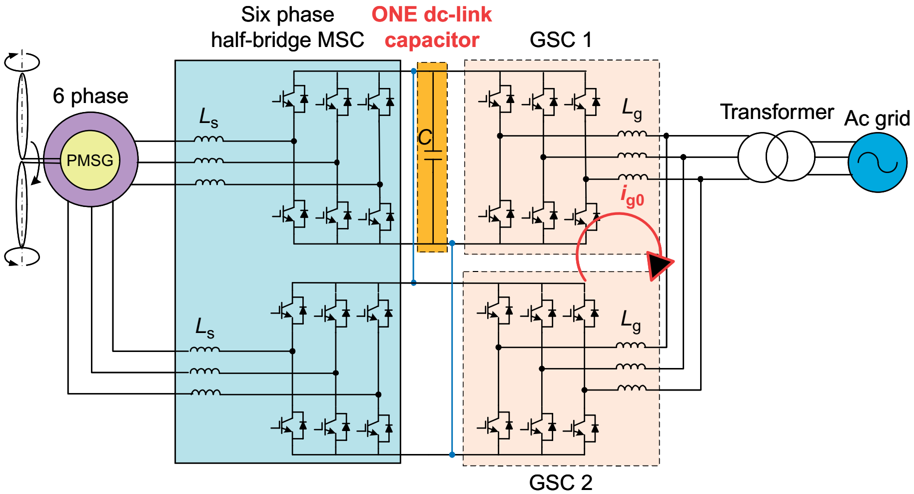
- Due to the sharing of controlled power in more converter legs, the DTP solution allows high-power (5-10 MW)/high current PMSG system with reduced current ratings of each power electronic devices, and as a result, the present power devices and well-proven commercial converters can be utilized.
- High reliability at system level is guaranteed due to the redundant structure, which means that fault tolerant operation is easy to be implemented.
- Torque pulsations at high frequency can be lowered.
- Higher power per ampere ratio for the same machine volume is achieved.
- Harmonic content of the dc-link current is reduced with one dc link employed, as shown in Figure 14(a).

4.4 Magnetic-geared PM machines

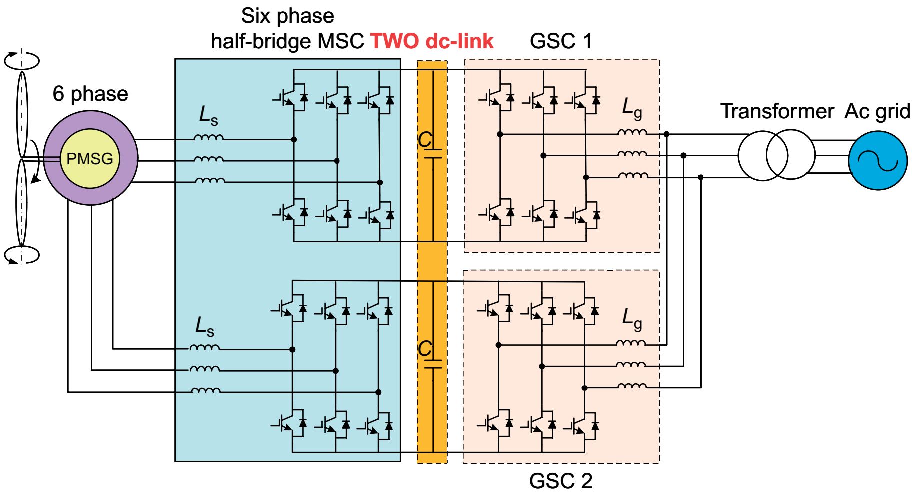
As shown in Figure 6, different types of generators, namely, SCIG, DFIG, EESG and PMSG, have been extensively utilized for wind power generation applications. However, mechanical gears are still widely and generally engaged to match the low-speed operation of the wind turbine with the relatively high-speed operation of the generators. This not only increases the cost of manufacture and maintenance but also reduces the efficiency and robustness, in particular for offshore wind farm applications.

In order to get rid of the nuisances caused by mechanical gears, the direct-drive PMSG and EESG, respectively, shown in Figure 6(d) and (f), have been employed for wind power generation systems by several turbine manufacturers (as outlined in Table I). Since the direct-drive generator has to operate at low speeds, it needs to have a bulky size with a very large number of pole pairs. Therefore, it is absolutely a tradeoff between the elimination of mechanical gears and the increase of machine diameter. Sometimes, the use of reduced-stage (single- or two-stage) mechanical gears plus a relatively medium-speed generator may have the reduction of overall size and weight as compared with the low-speed direct-drive generator.

Recently, the concept of magnetic gears was proposed and developed by Atallah and Howe (2001) and Rasmussen *et al.* (2005). In both papers, the torque was transmitted through a stationary segmented steel part having many poles with low magnetic reluctance. The idea with this part is to commutate the magnetic field from the low-speed side with many permanent magnetic poles (gear outer rotor) into the high-speed side with few poles (gear inner rotor), as shown in Figure 15(a).



(a) One dc-link for six-phase PMSG's machine-side converter and parallel-connected grid-side converter.



(b) Two dc links for six-phase PMSG's machine-side converter and parallel-connected grid-side converter

Figure 14.
Parallel connections of three-phase two-level low-voltage back-to-back voltage-sourced converters for a wind-turbine driven six-phase PMSG

The magnetic gear seems to have the following advantages when compared with classical mechanical gears (Rasmussen *et al.*, 2005), namely:

- no mechanical fatigue;
- no lubrication;
- overload protected;
- no mechanical contact losses;
- no mechanical contact acoustic noise;

- potential for very high efficiency (only a little core loss and bearing loss); and
- high torque per volume ratio (ten times standard motors).

More recently, the magnetic gear has been integrated into a PM motor to offer low-speed high-torque operation for electric vehicles (Chau *et al.*, 2007). Further, by incorporating the attractive features of both the outer-rotor PMSG and the magnetic gear, a magnetic-geared outer-rotor PMSG for wind power generation, as shown in Figure 15(b), was proposed and implemented (Jian *et al.*, 2009). A quantitative comparison illustrated that the magnetic-geared outer-rotor PMSG features smaller size and lighter weight than both the direct-drive PMSG and the planetary-geared PMSG, with lower material cost than the direct-drive one as well. Despite that the proposed generator and its prototype in Jian *et al.* (2009) were mainly used to illustrate the concept of magnetic gearing for wind power generation, this type of magnetic-geared outer-rotor PMSG with a full-capacity power converter may be highly competitive for wind power generation due to its other distinct merits as:

- the low-speed outer-rotor topology can enable direct coupling with the blades of wind turbines, so as to capture wind power with high efficiency;
- the integration of a coaxial magnetic gear can enable the PMSG to be designed for medium-/high-speed operation, hence achieving high power density and pretty small machine volume; and
- the use of the magnetic gear can provide physical isolation between its inner rotor as well as the generator's outer rotor (high speed) and the gear's outer rotor (low speed), thus minimizing the maintenance cost and the acoustic noise.

Off course, the structure of a magnetic-geared PMSG becomes much more complicated, its overall reliability may be reduced, and further the reduction of NdFeB magnets of PMSG as a result of increased operation speed may be a tradeoff by the extensive use of NdFeB magnets in the magnetic gear.

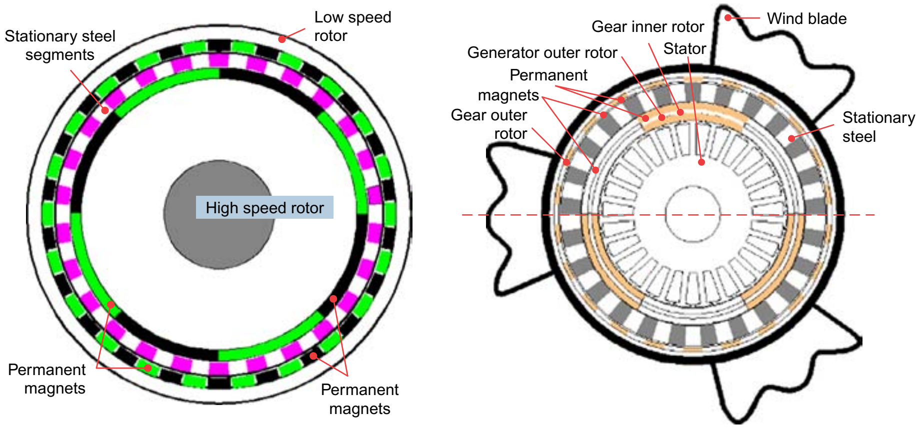


Figure 15.
(a) Cross-section of a magnetic gear (Atallah and Howe, 2001); (b) schematic configuration of a magnetic-geared outer-rotor wind-turbine driven PMSG (Jian *et al.*, 2009)

5. Conclusions

Wind energy has matured to a level of development at which it is ready to become a generally accepted power generation technology. This paper has briefly reviewed the latest market penetration and current technology of wind turbines, and identified the potential technology in the area of electrical machine systems for high-power wind energy generation applications.

For the time being, the gear-drive DFIG-based wind turbine is significantly dominating the markets, despite its obvious disadvantages arising from mechanical gears, slip rings and gear sets, and its sensitivity to grid disturbances that makes it a great challenge for LVRT operation to fulfill modern grid codes. Brushless DFIG has been reported to be capable of eliminating all the headaches caused by brushes and slip rings while keeping doubly fed operation. However, there exit a series of fundamental issues and challenges with respects to both design and control of the BLDFIG, which are of practical significance and application demanding. Meanwhile, direct-drive synchronous generator, especially utilizing PMs on its rotor, supplied with a full-capacity power converter has become a more effective solution compared with the DFIG-based system, particularly in high-power offshore wind farm applications, due to their low maintenance cost without mechanical gears and slip rings, complete decoupling from the grid, wider operating range and enhanced capability of fault ride through operation. Nevertheless, the PMSG's diameter is huge with multi-pole design, and initial cost is massive due to the high price of PMs. Tradeoff between the elimination of mechanical gears and the increase of generator size should be considered. Reduced-stage gear boxes can be a cost-effective solution, and magnetic-geared outer-rotor PMSG with full-power converter may be competitive for future wind power generation systems, but should be further studied in particular on a tradeoff between the reduction of NdFeB magnets of PMSG as a result of increased operating speed and the extensive use of NdFeB magnets in the magnetic gear.

References

Atallah, K. and Howe, D. (2001), "A novel high-performance magnetic gear", *IEEE Trans. on Magnetics*, Vol. 37 No. 4, pp. 2844-6.

Baiju, M.R., Mohapatra, K.K., Kanchan, R.S. and Gopakumar, K. (2004), "A dual two-level inverter scheme with common mode voltage elimination for an induction motor drive", *IEEE Trans. on Power Electronics*, Vol. 19 No. 3, pp. 794-805.

Boardman, G., Zhu, J.G. and Ha, Q.P. (2001), "Dynamic and steady state modeling of brushless doubly fed induction machines", *Proc. Fifth International Conference on Electrical Machines and Systems* (*ICEMS 2001*)*, Shenyang, China*, Vol. 1, pp. 412-16.

Brisset, S., Vizireanu, D. and Brochet, P. (2008), "Design and optimization of a nine-phase axial-flux PM synchronous generator with concentrated winding for direct-drive wind turbine", *IEEE Trans. on Industry Applications*, Vol. 44 No. 3, pp. 707-15.

Broadway, A.R.W. (1971), "Cageless induction machine", *Proc. IEE*, Vol. 118 No. 11, pp. 1593-600.

Broadway, A.R.W. (1974), "Brushless cascade alternator", *Proc. IEE*, Vol. 121 No. 12, pp. 1529-35.

BTM Consult Aps – A Part of Navigant Consulting (2011), "International wind energy department – world market update 2010 (forecast 2011-2014)", available at: www.navigant.com/~/media/site/downloads/energy/world_market_update_2010.ashx (accessed 30 April 2011).

Chau, K.T., Dong, Z., Jiang, J.Z., Chunhua, L. and Yuejin, Z. (2007), "Design of a magnetic-geared outer-rotor permanent-magnet brushless motor for electric vehicles", *IEEE Trans. on Magnetics*, Vol. 43 No. 6, pp. 2504-6.

China Guodian United Power – Proudct and Service (2011), available at: www.repower.de/index.php?id=12&L=1 (accessed 30 April 2011).

Creedy, F. (1920), "Some developments in multi-speed cascade induction motors", *Institution of Electrical Engineers, Journal*, Vol. 59 No. 301, pp. 511-37.

Dongfang Wind Turbines (2011), available at: www.dfstw.com/showProducts.aspx?articleid=272 (accessed 30 April 2011).

Enercon Wind Turbines, Product Overview (2011), available at: www.enercon.de/www/en/broschueren.nsf/vwwebAnzeige/15686F537B20CA13C125719400261D37/$FILE/ENE_Produktuebersicht_eng.pdf (accessed 30 April 2011).

Erhich, I., Winter, W. and Dittrich, A. (2006), "Advanced grid requirements for the integration of wind turbines into the German transmission system", *Proc. IEEE Power Engineering Society General Meeting, Montreal, Quebec*, p. 7.

Franklin, P.W. (1973a), "A theoretical study of the three phase salient pole type generator with simultaneous AC and bridge rectified DC output – part 1", *IEEE Trans. on Power Apparatus and System*, Vol. PAS-92 No. 2, pp. 543-51.

Franklin, P.W. (1973b), "A theoretical study of the three phase salient pole type generator with simultaneous AC and bridge rectified DC output – part 2", *IEEE Trans. on Power Apparatus and System*, Vol. PAS-92 No. 2, pp. 552-7.

Gamesa Wind Turbine Catalogue (2011), available at: www.gamesacorp.com/en/products/wind-turbines/catalogue (accessed 30 April 2011).

GE Wind Turbines (2011), available at: www.gepower.com/prod_serv/products/wind_turbines/en/index.htm (accessed 30 April 2011).

Goldwind Turbines Overview (2011), available at: www.goldwind.cn/en/index.asp (accessed 30 April 2011).

Gorti, B.V., Alexander, G.C. and Spee, R. (1996), "Power balance considerations for brushless doubly-fed machines", *IEEE Trans. on Energy Conversion*, Vol. 11 No. 4, pp. 687-92.

GWEC (2011), *Global Wind 2010 Report*, Global Wind Energy Council, available at: www.gwec.net/fileadmin/documents/Publications/Global_Wind_2007_report/GWEC%20Global%20Wind%20Report%202010%20low%20res.pdf (accessed 30 April 2011).

Holtz, J. and Oikonomou, N. (2010), "Optimal control of a dual three-level inverter system for medium-voltage drives", *IEEE Trans. on Industry Applications*, Vol. 46 No. 3, pp. 1034-41.

Hunt, L.J. (1914), "The 'cascade' induction motor", *Institution of Electrical Engineers, Journal*, Vol. 52 No. 230, pp. 406-34.

IEC Standard 61000-3-6 (1996), "Electromagnetic compatibility, assessment of emission limits for distorting loads in MV and HV power systems".

IEC Standard 61000-4-7 (1997), "Electromagnetic compatibility, general guide on harmonics and interharmonics measurements and instrumentation".

Jauch, C., Matevosyan, J., Ackermann, T. and Bolik, S. (2005), "International comparison of requirements for connection of wind turbines to power systems", *Wind Energy*, Vol. 8 No. 3, pp. 295-306.

Jian, L., Chau, K.T. and Jiang, J.Z. (2009), "A magnetic-geared outer-rotor permanent-magnet brushless machine for wind power generation", *IEEE Trans. on Industry Applications*, Vol. 45 No. 3, pp. 954-62.

Kato, S., Hoshi, N. and Oguchi, K. (2001), "A low-cost system of variable-speed cascaded induction generators for small-scale hydroelectricity", *Proc. IEEE IAS Annual Meeting, Chicago, IL, USA*, pp. 1419-24.

Kato, S., Michihira, M. and Tsuyoshi, A. (2006), "Modeling and simulation of a permanent magnet synchronous machine with six-phase stator winding for renewable energy applications", *Proc. Int. Conf. Electrical Machines Systems* (*ICEMS*)*, Nagasaki, Japan*, CD-ROM, Paper 204.

Kusko, A. and Somuah, C. (1978), "Speed control of a single-frame cascade induction motor with slip-power pump back", *IEEE Trans. on Industry Applications*, Vol. IA-14 No. 2, pp. 97-105.

Kwak, M.S. and Sul, S.K. (2008), "Control of an open-winding machine in a grid-connected distributed generation system", *IEEE Trans. on Industry Applications*, Vol. 44 No. 4, pp. 1259-67.

Levi, E. (2008), "Multiphase electric machines for variable-speed applications", *IEEE Trans. on Industrial Electronics*, Vol. 55 No. 5, pp. 1893-909.

McMahon, R.A., Roberts, P.C., Wang, X. and Tavner, P.J. (2006), "Performance of BDFM as generator and motor", *Proc. IEE EPA*, Vol. 153 No. 2, pp. 289-99.

Muller, S., Deicke, M. and De Doncker, R.W. (2002), "Doubly fed induction generator systems for wind turbines", *IEEE Ind. Appl. Mag.*, Vol. 8 No. 3, pp. 26-33.

Pena, R., Clare, J.C. and Asher, G.M. (1996), "Doubly fed induction generator using back-to-back PWM converter and its application to variable-speed wind-energy generation", *Proc. IEE EPA*, Vol. 143 No. 3, pp. 231-41.

Rasmussen, P.O., Andersen, T.O., Jorgensen, F.T. and Nielsen, O. (2005), "Development of a high-performance magnetic gear", *IEEE Trans. on Industry Applications*, Vol. 41 No. 3, pp. 764-70.

Roberts, P.C. (2004), "A study of brushless doubly-fed (induction) machines", PhD thesis, University of Cambridge, Cambridge.

Schiferl, R.F. and Ong, C.M. (1983a), "Six phase synchronous machine with AC and DC stator connections, part I: equivalent circuit representation and steady-state analysis", *IEEE Trans. on Power Apparatus and System*, Vol. PAS-102 No. 8, pp. 2685-93.

Schiferl, R.F. and Ong, C.M. (1983b), "Six phase synchronous machine with AC and DC stator connections, part II: harmonic studies and a proposed uninterruptible power supply scheme", *IEEE Trans. on Power Apparatus and System*, Vol. PAS-102 No. 8, pp. 2694-701.

Siemens Brothers & Co. Ltd Lydall, F. (1902), "Improvements in poly-phase induction motors", British Patent No.: 16839.

Siemens Wind Turbine Brochures (2011), available at: www.energy.siemens.com/hq/en/power-generation/renewables/wind-power/ (accessed 30 April 2011).

Singh, G.K., Yadav, K.B. and Saini, R.P. (2006), "Analysis of a saturated multiphase (six-phase) self-excited induction generator", *International Journal of Emerging Electric Power Systems*, Vol. 7 No. 2, pp. 1-21.

Sinovel SL1500/3000 Series Wind Turbines (2011), available at: www.sinovel.com/Products.html (accessed 30 April 2011).

Suzlon Product Brochures (2011), available at: www.suzlon.com/pdf/S88%20product%20brochure.pdf (accessed 30 April 2011).

Vestas Turbine Overview (2011), available at: www.vestas.com/en/wind-power-plants/procurement/turbine-overview.aspx#/vestas-univers (accessed 30 April 2011).

Vizireanu, D., Brisset, S. and Borchet, P. (2006), "Design and optimization of a 9-phase axial-flux PM synchronous generator with concentrated winding for direct-drive wind turbine", *Proc. IEEE IAS Annual Meeting, Tampa, FL, USA*, pp. 1912-18.

Vizireanu, D., Brisset, S., Kestelyn, X., Borchet, P., Milet, Y. and Laloy, D. (2007), "Investigation on multi-star structures for large power direct-drive wind generator", *Electric Power Components and Systems*, Vol. 35 No. 2, pp. 135-52.

Williamson, S., Ferreira, A.C. and Wallace, A.K. (1997), "Generalized theory of the brushless doubly-fed machine. Part 1: analysis", *Proc. IEE EPA*, Vol. 144 No. 2, pp. 111-22.

Xu, L. and Liu, H. (2009), "Rotor pole number studies for doubly excited brushless machine", *Proc. IEEE Energy Conversion Congress and Exposition* (*ECCE2009*)*, San Jose, CA, USA*, pp. 208-13.

Xu, L., Guan, B., Liu, H., Gao, L. and Tsai, K. (2010), "Design and control of a high-efficiency doubly-fed brushless machine for wind power generator application", *Proc. IEEE Energy Conversion Congress and Exposition (ECCE2010), Atlanta, GA, USA*, pp. 2409-16.

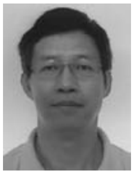
Appendix

Manufacturer	Type	Power	Voltage (kV)	Topology	Semiconductor	Control
ABB	ACS 1000	0.3-5 MVA	2.3;3.3;4.0;4.16	3-L-NPC-VSC	IGCT	DTC
	ACS 5000	1.7-24 MVA	4.16;6.0;6.6;6.9	5L-NPC-HB-VSC	IGCT	DTC
	ACS 6000	3-27 MVA	2.3; 3; 3.3	3-L-NPC-VSC	IGCT	DTC
Converteam	VDM 5000	1.4-7.2 MVA	2.3;3.3;4.2	2L-VSC	MV IGBT	VC
	VDM 6000	0.3-8 MVA	2.3;3.3;4.2	4L-FLC-VSC	MV IGBT	VC
	VDM 7000	7-9.5 MVA	3.3	3L-NPC-VSC	GTO	VC
		6/8 MVA			MV IGBT	
Siemens	Perfect Harmony	0.3-30 MVA	2.3-13.8	ML-SCHB-VSC	LV(MV) IGBT	VC
	Sinamics GM150	0.6-10.1 MVA	2.3;3.3;4.16;6;6.6	3L-NPC-VSC	MV IGBT	VC
	Sinamics SM150	5-28 MVA	3.3	3L-NPC-VSC	IGCT	VC
TMEIC GE[a]	Dura-Bilt5iMV	7.5 MW	4-4.2	VSI-3L-NPC	IGBT	N/A
	TMdrive-XL85	30-120 MVA	7.2	VSI-5L-NPC-HB	IGCT	
Allen Bradley	Power Flex 7000	0.15-6.7(22.5) MVA	2.4;3.3;4.16;6.6	PWM-CSI	SGCT	VC

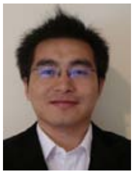
Note: [a]Association between General Electric, Toshiba and Mitsubishi Electric

Table AI.
Market overview of industrial multilevel MV PWM drives

About the authors



Z.Q. Zhu received the BEng and MSc degrees in Electrical and Electronic Engineering from Zhejiang University, Hangzhou, China, in 1982 and 1984, respectively, and the PhD degree in Electrical and Electronic Engineering from the University of Sheffield, Sheffield, UK, in 1991. From 1984 to 1988, he was a Lecturer with the Department of Electrical Engineering, Zhejiang University. Since 1988, he has been with the University of Sheffield, where he was initially a Research Associate and was subsequently appointed to an established post as Senior Research Officer/Senior Research Scientist. Since 2000, he has been a Professor of Electrical Machines and Control Systems with the Department of Electronic and Electrical Engineering, University of Sheffield, and is currently Head of the Electrical Machines and Drives Research Group. His current major research interests include design and control of permanent magnet brushless machines and drives, for applications ranging from automotive and aerospace to renewable energy. He is a Fellow of IEEE. Z.Q. Zhu is the corresponding author and can be contacted at: Z.Q. Zhu@sheffield.ac.uk



Jiabing Hu received the BSc and PhD degrees from the College of Electrical Engineering, Zhejiang University, Hangzhou, P.R. China, in July 2004 and September 2009, respectively. From 2007 to 2008, he was as a Visiting Scholar with the Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK. He is currently a Post-Doctoral Research Associate with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, UK. His current research interests include motor drives, digital control and application of power electronics in renewable energy conversion, especially the control and operation of doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) for wind power generation. He is a Member of IEEE.