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Chapter 3

POWER ELECTRONICS TECHNOLOGY: ENABLING LARGE-SCALE INJECTION OF WIND ENERGY INTO THE GRID

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ABSTRACT

The growing demand for a sustainable energy supply is motivating worldwide interests in renewable power technologies. The wind is the most promising renewable source globally, leading other sources in making the surroundings cleaner and more environmentally friendly, creating new jobs and industries, as well as in the combat against water crises – preserving the fresh water resources. The addition of wind energy into the electricity grid can severely influence the monetary cost, quality and stability of the grid network owing to the unpredictable nature of wind. Moreover, the electricity grid has limited control functionalities to absorb, cope with or switch large-scale wind power. Power electronics and advanced control technologies can enable optimum transfer of

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suitable and applicable wind power into the electricity grid, but the wind turbine technology is influenced strongly by the power demand, the type of generator utilised and the requirements of the electricity grid. Improvements in the efficiency of power electronic systems with enhancing control capabilities (reliability, durability and power ratings) can smooth the progress of large-scale injection of wind energy into the grid in the future. This chapter investigates the prospects of a key enabling technology for large-scale injection of wind turbine energy to the electric power grid.

Keywords: electric power grid, power converters, power electronics, renewable energy, wind power generation system, wind turbine

INTRODUCTION

The world electricity demand is rapidly increasing due to its fast growing population. As shown in Table 1, a projected growth of 48% in energy demand is anticipated by 2040 with most of the rise coming from the non-OECE (Organisation for Economic Cooperation and Development) countries, including China and India while African’s electricity demand, which is already blowing up, is estimated to quadruple by 2100 (http://www.eia.gov/forecasts-/ieo/; accessed December 20, 2016). According to the Africa Energy Sector Outlook (AESO)-2040, an estimate of 587 million people (≈ 42% of global population) without access to electricity lives in Africa. In particular, over 93 million people cannot access electricity in the most populous African country (Nigeria). In spite of this drawback, electricity supply is not reliable and can only be accessed for an average of 6 hours per day (Okundamiya, 2015). On the other hand, if the electric power required to cater to the electricity demand in regions without access to electricity were to come from fossil fuels, it could hinder global efforts to reducing global warming. As a result, sustainable energy technology has become a key requirement of the civilised society in alleviating the challenges of increased energy demand.

Table 1. World energy consumption by power source from 1990 – 2040 (quadrillion Btu)

	Year	Liquid Fuels	Coal	Natural Gas	Renewable	Nuclear
History	1990	137.43	89.24	75.28	33.69	20.36
	1992	139.26	82.00	77.03	34.82	21.28
	1994	141.78	84.30	78.90	36.76	22.41
	1996	147.45	89.16	83.28	39.15	24.11
	1998	151.49	86.85	84.16	39.93	24.31
	2000	157.01	96.45	89.78	40.90	25.65
	2002	159.37	100.59	94.07	41.50	26.67
	2004	168.09	118.47	100.05	44.01	27.25
	2006	173.40	133.15	105.17	47.30	27.67
	2008	173.81	142.24	112.23	52.53	27.03
	2010	178.54	145.92	118.29	57.72	27.38
	2012	183.55	153.27	124.21	63.77	24.47
Projections	2014	187.87	160.26	128.03	68.05	25.21
	2016	192.68	161.72	131.51	74.46	27.76
	2018	198.24	165.59	133.99	79.63	29.53
	2020	204.17	168.62	138.28	86.99	30.90
	2022	207.42	170.71	144.08	92.58	32.92
	2024	210.70	172.61	151.19	96.95	33.58
	2026	214.30	173.41	158.41	100.70	35.66
	2028	217.88	174.00	165.77	104.35	38.13
	2030	221.80	174.45	173.14	108.14	40.21
	2032	226.19	175.26	180.72	112.84	41.75
	2034	230.76	176.29	188.42	117.25	42.99
	2036	235.76	177.48	196.39	121.74	43.87
	2038	240.97	178.66	204.24	126.51	44.89
	2040	246.04	180.18	211.39	131.36	45.98

Renewable energy sources are becoming a major contributor to the electricity grid. According to the Medium-Term Renewable Energy Market Report (MTREMR), the portion of renewable sources in worldwide power generation is growing to 28% by 2021 from approximately 22% in 2013 making renewable the fastest-growing source of power generation. By 2021, the capacity of worldwide electricity generation from renewable sources will be equivalent to the current combined electricity generation by the European Union and the United States (more than 60% rise in global energy generation over the medium term) (IEA, 2015; IEA, 2016). The rising demand for renewable energy technology is motivated by the need for energy sustainability. The wind is leading other renewable power sources in mitigating the effects of climate change and in the creation of more industries as well as employment opportunities. Furthermore, wind energy is a rising contributor to the decline in CO_2 emission and has generated more new electric power than any other technology globally. Nevertheless, due to the uneven characteristic of the wind, the system electric power output exhibit variability, which creates a burden on the reliability, security, quality and stability of the grid network (Okundamiya, 2015; Okundamiya & Omorogiuwa, 2016). Reliability and affordability of electric power are, in particular, an essential component for sustainable development in virtually all segments of the economy (Okundamiya & Omorogiuwa, 2015). Consequently, the strategy for efficient control and injection of wind energy to the grid is a crucial aspect towards ensuring the economic and technical viability of grid integrated wind power systems.

Wind energy can be transferred into the grid using power electronics, as illustrated in Figure 1. The principal goal of the Wind Energy Conversion System (WECS) is to harness the wind turbine energy – change the kinetic energy from wind to electric power and subsequently injects the electric power into the grid (Pavalam, Kumar & Umadevi, 2014; Dargahi et al., 2015). The power electronic technology helps in the processing of the electric power by means of power semiconductor devices. The framework signifies the focal point where electronics, power systems and control engineering converge and combine. In addition, power electronic technology provides functionalities that affect wind sources for optimum energy harvest and power support to the electricity grid. The technology is required to modify the dynamics of wind resources to the human application because the natural forms are not displaceable and the energy generated needs to be stored or directly transferred into the grid. One of the major drawbacks of wind power potential in Africa is the dearth of robust utility grid for large-scale integration of wind energy (Okundamiya, 2016).

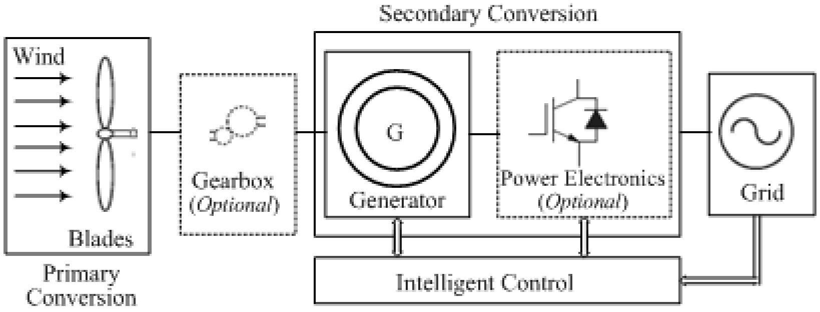

Figure 1. The basic elements of a wind turbine energy conversion system.

This chapter describes the requirements, control and standards of wind power conversion system, and the concepts of power electronic technology for interfacing wind energy into the electric power grid. The next section centres on the state of the art assessment of the wind power conversion technology. It gives a description of the status of the wind turbine power – installation/generation capacity, technology, standards and challenges for grid integration – with important statistics indicating the increasing role of wind power generation in recent times. The third section discusses the power electronic technologies for grid interfacing of the wind turbine power system. The control techniques for a modern wind power system are discussed in section 4 while the conclusion of this study is presented in section 5.

WIND ENERGY CONVERSION TECHNOLOGY

The wind has advanced into a mainstream energy source, with the rapid expansion of the wind power industry across Asia, Africa and Latin America; intense and unrelenting commitment from China and India; exceptionally stable policy framework in the United State’s market; and the rapidly reducing costs of wind energy for both onshore and offshore. The cost of the onshore wind energy has reduced considerably and onshore wind power technology is at present considered as the utility alternative of choice – cheapest way to enhance the capacity of the grid in a large number of markets.

Status of Wind Turbine Power (GWEC, 2016; 2017)

Wind supplies ~4% of worldwide electricity supply and are fast growing. Wind power contributed a significant portion of the recently installed capacity. In 2015, wind generated almost 50% of the cumulative increase in electric power production globally. In particular, wind power generated in Scotland, on a stormy day in August, exceeded the total electricity demand for that day. Denmark electricity supply constitutes over 40% of wind power, South Australia (~40%), Ireland and Portugal (23%), Uruguay (~20%), Spain (19%) and Germany (15%). In the same vein, the contribution of the wind to the total power generation of the US state of Texas is 10%, Oklahoma 18%, Kansas 24%, South Dakota 25% and Iowa 31%. The United States currently generates 250% new wind power than it did 5 years ago. Moreover, the number of people employed by the wind power industry across the globe exceeds 1 million at the end of 2015.

Table 2 shows the world annual and cumulative onshore installed wind capacity during the last 10 years. As observed, the world wind power industry added annual installations of 54.6 GW to achieve a cumulative global power generation capacity of approximately 486.7 GW in 2016 (compared to the cumulative capacity of ~432.7 GW in 2015). Asia led the wind industry (total installed capacity of over 203.6 GW), next Europe (161.3 GW) and North America (97.6 GW) with second and third positions respectively and emerging markets across Latin America, Asia and Africa. In terms of new capacity installations, China maintained its first position – largest global wind power market – followed by the United States of America, Germany, India and Brazil. Table 3 shows the top 10 new installed onshore wind power capacity market for the period (January – December 2016).

In 2015, China and India increased its wind power capacity by 30.8 and ~25.1 GW respectively; while the corresponding additional capacity installation in 2016 decreased to 23.3GW and 3.6GW as shown in Table 3. In addition, fresh wind power markets such as Indonesia, Mongolia, Vietnam, Pakistan and Philippines are rapidly developing in Asia. Conversely, Germany keeps leading the EU (European Union) with a total wind power installed capacity of 50.0GW, followed by Spain (~23.1GW), UK (14.5GW), France (~12.1GW) and Italy (~9.3GW) as shown in Table 4 while Denmark, Portugal, Poland and Sweden each have over 5GW of wind power installed at the end of 2016. Away from the EU, Turkey has the largest total installed capacity in excess of 6GW in Europe. The US leads in Americas, with a total wind power installed capacity of about 82.2GW while Canada (now the eighth largest market globally, being displaced by France) has total installed capacity of 11.9 GW and Mexico installed 454MW of wind power to arrive at a total capacity in excess of 3.5GW. Table 4 shows a comparison of the top 10 cumulative onshore wind power installed capacity between 2015 and 2016.

Table 2. World annual and cumulative onshore installed wind power capacities (2007 – 2016)

Year	**Installed Capacities (MW)**	
	Annual	**Cumulative**
2007	20,310	93,924
2008	26,850	120,696
2009	38,475	159,052
2010	39,062	197,956
2011	40,635	238,110
2012	45,030	282,850
2013	36,023	318,697
2014	51,675	369,862
2015	63,633	432,680
2016	54,600	486,749

Table 3. Top 10 new installed onshore wind power capacity from January – December 2016

Country	**New Installed Capacity**	
	MW	**% Share**
China[1]	23,328	42.7
USA	8,203	15.0
Germany	5,443	10.0
India	3,612	6.6
Brazil[2]	2,014	3.7
France	1,561	2.9
Turkey	1,387	2.5
Netherlands	887	1.6
United Kingdom	736	1.3
Canada	702	1.3
Total Top 10	**47,873**	**87.7**

[1] Interim figure; [2] Projects commissioned with grid connectors pending in some cases.

Table 4. Top 10 cumulative onshore wind power capacities at the end of the year 2016

Country	Cumulative (End 2015)		Cumulative (End 2016)	
	MW	% Share	MW	% Share
China[1]	145,362	33.6	168,690	34.7
USA	73,991	17.1	82,184	16.9
Germany	44,941	10.4	50,018	10.3
India	25,088	5.8	28,700	5.9
Spain	23,025	5.3	23,074	4.7
United Kingdom	13,809	3.2	14,543	3.0
France	10,505	2.4	12,066	2.5
Canada	11,219	2.6	11,900	2.4
Brazil[2]	8,729	2.0	10,740	2.2
Italy	8,975	2.1	9,257	1.9
Total Top 10	**365,644**	**84.51**	**411,172**	**84.47**

[1] Interim figure; [2] Projects commissioned with grid connectors pending in some cases.

In the same vein, Brazil leads the Latin American and Caribbean's market with cumulative installations of over 10.7GW. Uruguay and Chile have a total installed capacity that exceeded 1GW each, Costa Rica (298MW), Argentina (279MW), Panama (270MW) and Honduras (176MW) at the end of 2016. It is worth mentioning that China's total wind power capacity (168.7GW) exceeds the total wind power installations (153.7GW) of all EU countries.

Australia leads the Pacific region with total installed wind capacity of over 4.3GW by the end of 2016. At the same time, Africa and Middle East region installed additional wind power of 418MW to reach a cumulative capacity exceeding 3.9GW. South Africa is leading the region with cumulative installed capacity of more than 1.4GW, followed by Egypt (810MW), Morocco (787MW), Ethiopia (324MW), Tunisia (245MW), Jordan (119MW) and Iran (91MW), while the installed capacities in Cape Verde, Kenya, Israel and Algeria are each below 25MW towards the end of 2016.

In contrast, the world offshore wind power industry installed over 3.4GW and 2.1GW across five markets in 2015 and 2016 respectively, with a total offshore wind power capacity of more than 14.3GW at the end of 2016. Over 12GW (>87%) of the offshore wind turbine power installations were positioned in eleven European countries with the left over installed capacity largely situated in China, followed by Japan, South Korea and the USA. However, the United

Kingdom accounts for more than 35% of the offshore wind installed capacity, followed by Germany (28.6%), Denmark (8.8%), Netherlands (7.8%), Belgium (~4.9%), Sweden (1.4%) and other EU countries (including Ireland, Finland, Norway and Spain) constitute approximately 0.5%. Outside of the European waters, the largest market is China (~11.3% of the global market). Table 5 shows a 2 year (2015 and 2016) comparison of the cumulative offshore wind power installed capacity for different markets across the globe.

Table 5. Comparison of the 2015 and 2016 cumulative offshore wind installed capacity for different market across the globe

Country	**Installed Capacity (MW)**		
	Cumulative at end of 2015	**New at end of 2016**	**Cumulative at end of 2016**
United Kingdom	5,100	56	5,156
Germany	3,295	813	4,108
China	1,035	592	1,627
Denmark	1,271	0	1,271
Netherlands	427	691	1,118
Belgium	712	0	712
Sweden	202	0	202
Japan	53	7	60
South Korea	5	30	35
Finland	32	0	32
USA	0.02	30	30
Ireland	25	0	25
Spain	5	0	5
Norway	2	0	2
Total	**12,164**	**2,219**	**14,383**

Wind Turbine Technology

Wind turbines are classified based on mechanical structure as vertical-axis and Horizontal-Axis Wind Turbine (HAWT) (Babu & Arulmozhivarman, 2013). The HAWT designs, which modern wind turbines utilise, are modelled for either a fixed-speed or a variable-speed operation. It is to be noted that variable-speed wind turbine has higher efficiency, and lower cost-to-power ratio with reduced noise and mechanical stress compared to the fixed-speed configuration. In addition, variable-speed turbines can trace the optimum power extraction point, hence, can generate more power than constant-speed type, but it requires advanced power electronics and intelligent control circuitry to provide constant frequency and power factor (Okundamiya, 2016).

The generators utilised for the WECS are either Permanent Magnet Synchronous Generators (PMSGs) or Doubly-Fed Induction Generators (DFIGs). The DFIG technology is mostly employed for wind power conversion because of its benefits in monetary cost, size and weight but the reliability of the gearbox, brushes and slip rings is not suitable for certain applications. Previous designs based on DFIG technology (with only the rotor circuitry utilising a downgraded power electronics converter, whereas the stator winding is linked to the AC line) are being substituted with modern designs with full-scale power electronic converters in addition to induction generators, wound field synchronous generators or PMSGs (Blaabjerg & Ionel, 2015). The permanent magnet synchronous generator has higher efficiency and less maintenance since it does not need a gearbox. In addition, the generator drives realise a very high torque at low speeds with a reduced amount of noise and do not need external excitation (Ajami, Alizadeh & Elmi, 2016). Multi-pole PMSGs with full-scale back-to-back power converters tend to be the future topology to be adapted by most wind turbine manufacturers, gradually replacing DFIG in wind energy conversion (Vilathgamuwa & Javasinghe, 2012; Okundamiya, 2016). Table 6 shows a comparison of the specifications of the 10 leading wind turbine suppliers in 2015, based on the current global wind energy research.

Among the key enabling factors of the advancement of wind power technology are variable-speed operation of wind turbine generators to extract maximum energy, economy of scale attributable to availability of large wind power plants, accrued field knowledge improving the capacity factor, improvements in power electronic devices and circuits in addition to the declining associated monetary cost, and computer prototyping by means of precise system modelling and simulation. Moreover, the cost of wind turbine power across Africa, South America and the United States is reducing. For example, the cost of wind energy in the United States has decreased by over 65% in the past 6 years. A key factor of cost reductions is the advances in the wind power conversion technology – with larger wind turbine size (higher hub heights and larger rotor diameters) and enhanced power conversion process in place.

Table 6. Comparisons of top 10 wind turbine supplies in 2015

No. (Share)	Manufacturer (Country)	Model	Generator Power	Status (year)	Size MW/m	Output Voltage (Frequency)	Grid Connection	Market
1 (12.8%)	Goldwind (China)	GW6000MW	PMSG	PI (2014)	6.0/150	690V (50/60 Hz)	Full power converter	offshore
		GW3000MW	PMSG	N/A	3.0/110	690V (50/60 Hz)	Full power converter	N/A
2 (12.0%)	Vestas (Denmark)	V164-8.0MW	PMSG	CA (2016)	8.0/164	650V (50 Hz)	Full power converter	offshore
		V126-3.3MW	PMSG	CA (2013)	3.3/126	650V (50 Hz)	Full power converter	onshore
3 (9.2%)	GE Energy (US)	GE4.0-110	PMSG	N/A	4/110	650V (50/60 Hz)	Full power converter	N/A
		GE2.75-120	PMSG	CA (2014)	2.75/120	650V (50/60 Hz)	Full power converter	onshore
4 (7.7%)	Siemens (Germany)	SWT-8.0-154	PMSG	PI (2017)	8.0/154	690V (50 Hz)	Full power converter	offshore
		SWT-6.0-154	PMSG	CA (2014)	6.0/154	690V (50 Hz)	Full power converter	offshore
5 (5.5%)	Gamesa (Spain)	G128-5.0 MW	PMSG	CA (2015)	5.0/128	690V (50/60 Hz)	Full power converter	offshore
		G114-2.0 MW	DFIG	CA (2014)	2.0/114	690V (50/60 Hz)	IGBT converter	onshore
6 (5.1%)	Enercon (Germany)	E-126/7.5MW	EESG	CA (2010)	7.58/127	400V (50/60 Hz)	Full power converter	onshore
7 (4.7%)	United Power (China)	UP3000-100	DFIG	PI (2011)	3.0/100	690V (60 Hz)	Direct connection	onshore
8 (3.8%)	Ming Yang (China)	6.5MW SCD	PMSG	CA (2014)	6.5/140	N/A	Full power converter	offshore
9 (3.5%)	Envision (China)	E3.6-128	PMSG	N/A	3.6/128	730V	IGBT converter	offshore
10 (3.4%)	CSIC Haizhuang (China)	HZ-5MW	PMSG	CA (2015)	5.0/154	N/A	Full power converter	offshore

CA: Commercially available; PI: Prototype installed; NA: Not available

In spite of the recent improvements in wind power technology, investigations are still on-going to extract the highest amount of energy from wind. The use of wind turbines mounted on taller towers with longer blades and generators with lower cut-in speeds, for instance, generate more energy at high capacity factors in modest wind regimes closer to load centres and this can lead to further reduction in the cost of wind power (GWEC, 2016).

Standards for Grid Integration

Wind Turbine Generators (WTGs) are a fragment of utilities with possible sources of low power quality. The standards based on International Electrochemical Commission (IEC) for the measurement and evaluation of the power quality requirements of grid-coupled WTG consist of three parts – harmonic, switching and flicker analyses. Essentially, the flicker analysis makes use of voltage and current time series measured at the terminals of the wind turbine to simulate voltage variations on a fabricated grid with no source of voltage fluctuation (Carrasco et al., 2006). Besides, current and voltage transients are measured in the course of switching of the WTG while harmonic analysis is performed by the Fast Fourier Transform Algorithm (Jain, Jain & Nema, 2015). A detailed description of these methods is presented in the literature.

Wind turbines should supply power (active/reactive) for voltage and frequency recovery, instantly after the occurrence of a fault. The fault-ride standard stipulates that during fault occurrence, a WTG should stay steady and connected when the voltage at the point of connection falls to 15% of the nominal voltage for a period of 150ms (Zhu & Hu, 2013). In addition, when the voltage is within the safe operating area – as described by the fault-ride through the potential curve of wind turbines linked to the utility grid – the WT should supply reactive power to the electric power grid so as to sustain grid-voltage restoration. The wind turbine can disconnect from the electricity grid when the grid voltage falls below the fault ride through capability curve (Carrasco et al., 2006).

Meanwhile, despite the International Standards, special grid connection codes (such as the E.ON-Netz, 2008) are available, which define the effective limit of a WTG connected to the grid in terms of voltage acceptance, frequency range, fault-ride through and power factor. These codes try to make the wind turbine power conversion system prudently control the distributed power (active/reactive) based on the demand and to supply voltage and frequency assistance for the electric power grid. Moreover, the wind turbine must be able to control the active power at the Point-of-Common-Coupling (PCC) (Ma et al., 2015). Grid codes vary among transmission operators. In addition, it focuses on the testing approach utilised for validating the fault-ride through potential of wind turbines and their performance for the period of a grid fault (Ayodele et al., 2012). The development of stricter grid codes in the future could lead to an improved wind power conversion system with highly advanced power electronic technology.

The requirements of WTGs for fault-ride through capability and enhanced power quality have raised the cost of wind energy per kWh, although more suitable wind energy are being extracted and interfaced with the utility grid.

Challenges of Grid Integration of Wind Energy

Searching for greener and more reliable energy has a knock-on effect on the quality and reliability of energy transferred to the grid. The quality of power injected into the grid refers to the degree of variation from the standard sinusoidal (voltage and current) waveforms in the utility grid network (Ayodele et al., 2012). The level of acceptance depends on the sensitivity of the load demand but it is worthy of mention that the key components, which ascertain the power system quality include harmonic distortions, flickers and voltage imbalance (Okundamiya, 2016).

The power electronic converters employed by variable-speed WTGs produce harmonics particularly in electricity grids with low short-circuit capability. Current forced-commutated inverters utilised in variable-speed turbine applications generate both harmonics and inter-harmonics (Carrasco, Galvan & Portillo, 2014). In contrast, the utilisation of fixed-speed WTGs causes flickers on the grid. Harmonics result in excessive heating of equipment and this reduces components life span while flickers cause imbalance and core saturation of transformers, and create an uncomfortable visual effect on the eyes, as well as thermal ageing of induction motors. Poor quality of electric power often results in energy losses, malfunctioning of equipment and perhaps, power system failure.

The output of a WTG varies strongly according to the wind regime in addition to the performance characteristics and the efficiency of the wind turbine power generation system (Okundamiya & Nzeako, 2013). Electric power system operators and planners are concerned about the variations of wind resource and the associated economic impacts on the power system stability when integrated into the grid. Power imbalance affects the frequency of an electric power grid, which can result in loss of synchronisation. The realisation of power balance between the generating plants and the load is more demanding for wind power production especially when the generating ratio is high. Induction generators commonly used for most wind power applications are unable to transfer reactive power into the grid and this impedes wind energy system interface with the grid.

The failure of the WECS will impose strong impacts on the stability of the grid, which results in increased cost to repair; thus the reliability performance of wind power systems is especially emphasised. In addition, energy storage and balancing as well as cooling capability and power density are an essential performance for wind power conversion system. As a result, the requirements for efficient and reliable transfer of wind energy into the electricity grid introduce additional demands such as dynamic grid support, effective protection, system monitoring and communication, and the control of power transferred into the electricity grid.

POWER ELECTRONIC TECHNOLOGY FOR WIND ENERGY INTEGRATION

The current trend of renewable power generation requires a modern approach to the operation and efficient management of the electric power grid as this could enhance the quality and reliability of power supply (Carrasco et al., 2006). Power electronic technology performs a significant task in wind energy integration to the grid. Highly efficient and exceedingly reliable power electronics systems are required for interfacing wind energy to the grid, as well as to enable enhanced auxiliary functions such as Low-Voltage Ride-Through (LVRT) capability and grid assistance with reactive power injection (Blaabjerg, Ma & Yang, 2014a).

Power Electronic Converter Topologies

Power electronics combined with advanced control systems are utilised as AC–DC–AC converters. The choice of power electronic converter for a WTG is influenced by the energy demands, the type of generator utilised and the grid requirements.

Variable-Speed Wind Turbines Technology

Among the widely utilised wind turbine system design configurations, the variable-speed WTGs (with partial-scale and full-scale power converters as depicted by Figure 2) are presently domineering the markets (Okundamiya, 2016). In variable-speed wind turbine topology, power electronics partly or fully decouple the rotor mechanical frequency from the grid electrical frequency to enable variable-speed operation. The configuration illustrated in Figure 2a comprises a 3-phase wound rotor generator (stator windings being fed from the electricity grid and rotor windings are fed by means of a back-to-back power electronic converter) in a bidirectional feedback loop. The electrical rotor frequency of the DFIG can be varied when the power electronic converter supplies the rotor windings with the stator windings linked directly to the electric power grid, enabling variable-speed operation. The converter size is noticeably smaller than the rated capacity of the turbine generator utilised, which prevents full range operation, although the speed range is fairly adequate and losses are minimised (Okundamiya, 2016).

In contrast, the generator is wholly decoupled from the electric grid in the full-scale converter configuration as shown in Figure 2b. Wind turbines are mostly equipped for full-power converter operation, with multi-pole synchronous generators, due to increased reliability, reduction of monetary costs and losses, compared to the gearbox-based induction generator configurations. The configurations described in Figure 2, also known as the back-to-back two-level voltage source converters, show fast control of the power flow and can supply harmonic compensation and reactive power control to both power converters (grid-side and rotor-side) (Blaabjerg et al., 2011). The goal of the grid-side converter is to attain a voltage, which satisfies the current demand on the generator while the rotor-side power converter is to meet the current demand on the grid-side. The DC-link, comprising an energy storage element, helps to realise the current flow between the rectifier and the inverter. The link smoothens the converter's DC output ripple, provided the duration of the time constant ($\tau = RC$) is much longer than that of one ripple cycle.

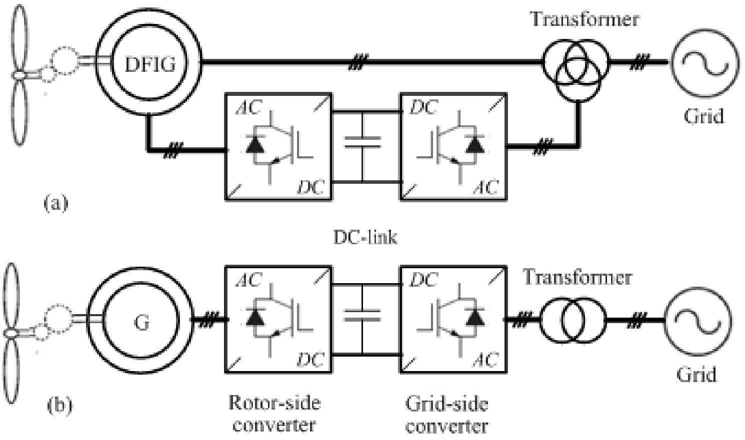

Figure 2. Variable-speed wind turbine topologies with (a) Partial-scale power converter and (b) Full-scale power converter.

Onshore versus Offshore Wind Turbine Technology

The energy balance of offshore wind turbines can be more beneficial than onshore turbines; these advantages depend on the local meteorological conditions. The offshore topology is more durable, about 25–30 years due to lesser fatigue loads on the turbine resulting from low turbulence from the sea (Carrasco et al., 2006). However, the maximum possible length and transmission capacity of Heating-Ventilation-Air Conditioning (HVAC) cables is restricted for offshore applications. High-Voltage Direct-Current (HVDC) transmission technology is mostly competitive at transmission lengths in excess of 100km or power levels in the range of ≈ 200 to 900MW (Franquelo & Leon, 2013). The HVDC transmission presents several benefits compared to the HVAC, namely: independent sending and receiving frequencies, mainland disturbances are isolated from offshore installation and vice versa. In addition, the power flow is controllable and entirely defined, power transmission capacity per cable is higher and power losses of cable are low (Kumar et al., 2011). In the classical LCC (Line Commutated Converter)-based HVDC transmission system design, the thyristors require an AC voltage source to facilitate commutation and can only transmit power amid two active AC networks (Franquelo & Leon, 2013). In addition, the LCC-based HVDC transmission schemes generate considerable amounts of harmonics; hence, the utilisation of bulky filters is unavoidable and lacks the possibility to offer an autonomous power monitoring and control. As a result, they are rarely used in wind farms.

Voltage Source Converter (VSC)-based HVDC transmission technology is attracting significant attention for injection of large-scale onshore and offshore wind power systems with utility grids. This technology is made possible by the Insulated Gate Bipolar Transistor (IGBT) device, which can switch-off currents. This property eliminates the necessity of an active commutation voltage. As a result, VSC-based HVDC system does not need a robust onshore or offshore AC network. Moreover, the system can start up against a dead network (Carrasco et al., 2006). The active and reactive powers, when controlled separately, can lessen the demand for reactive power compensation, which helps to stabilise the AC network at the PCC as depicted in Figure 3.

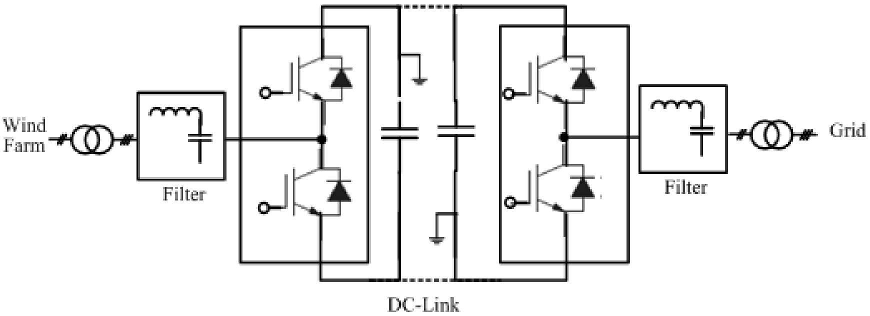

Figure 3. VSC-based HVDC transmission scheme.

Medium-Voltage High-Power Wind Energy Technology

The multi-level power converter topologies are mainly categorised into five multi-level configurations comprising (Hu, Li & Xu, 2008): bi-directional switch interconnection, diode clamped, capacitor clamped, and multiple 3-phase inverters and cascaded 1-phase H-bridge inverters. In theory, these configurations can be constructed with *n* levels (randomly chosen) but in reality, some designs are easier to implement than others. In addition, the multi-level converter has the least demand for input filters. For a similar harmonic content as a two-level power electronic converter, the switching frequency of a multi-level power converter can be decreased by 75%, which leads to lower switching losses (Foussekis et al., 2003).

Although the multi-level converter has higher conducting losses, overall efficiency varies with the ratio of switching to conducting losses. The rise in voltage rating permits direct link between the power electronic converter and the wind turbine energy system, thus, eliminating the use of large transformers. The main shortcoming of the multi-level topology is the need to attain different independent sources DC voltage required for the multi-level modulation. The utilisation of low-speed Permanent-Magnet Generators (PMGs) with a large number of poles permits DC sources to be obtained from the multiple wounds of the electric power machine (Foussekis et al., 2003). The multi-level cascaded topologies are mostly used for industrial applications due to the continuous decrease of the unit cost of the power electronic building blocks.

Direct-Drive Wind Turbine Technology

The direct-drive technology is growing due to the exclusion of the gear box. The direct-drive generator reduces the total size, lowers the installation and maintenance cost, offers a variable control technique and rapid response to wind variations and load fluctuations. Different concepts for direct-drive generators are available in the literature for grid-integrated WECS. Chang, Wang and Song (2004) gave a description of a low-speed direct-drive PMG for WECS applications. A common trend for propulsion system applications is the utilisation of an axial flux machine, which is employed in small-scale direct-drive WTGs since larger torque density can be attained conveniently (Bumby & Martins, 2005).

Advances in Semiconductor Technology

The essential performance characteristics of power electronics for wind power applications are directly related to the viability of power semiconductor devices with improved electrical properties at reduced cost. The rapid advancement of power electronics in recent times is due to the development of semiconductor devices with fast switching speed and high power handling capability as well as the establishment of real-time computer controllers capable of implementing intelligent control algorithms. The monetary cost of power semiconductor devices is declining, 1-5% per annum for similar output performance; hence, the cost of power electronics technology is also decreasing (Carrasco, Galvan & Portillo, 2014). The potential silicon-based semiconductor technologies include the Integrated Gate Commutated Thyristor (IGCT) and the IGBT.

The IGBT is a special class of transistor with similar function as a BJT but its base is driven by a field-effect transistor while the IGCT is a part of a larger family of combination devices, in which multiple semiconductor chips are packaged together to carry out a single power function (Krein, 2011). The IGBT technology can adapt to a very high-power range (from 1 to 200kW) and can favourably compete with the gate turn-off thyristors for high power applications. The IGBT exhibits superior qualities for frequency converters in WECS applications. The switching frequency is higher compared to IGCTs, which results in a lessened amount of distortion in the electric power grid. In addition, the modular packaged IGBT silicon chip is separated from the cooling plate, which can be linked to the ground to permit low electromagnetic emission even with higher switching frequency (Carrasco, Galvan & Portillo, 2014). This configuration results in negligible thermal stress and increased the lifespan of the device by approximately ten folds.

In contrast, heating and cooling of the IGCT can mechanically stress the silicon chip making the device to exhibits high electromagnetic emission. Consequently, the lifespan of the IGCT is significantly reduced, particularly for wind turbine applications. Nevertheless, the main advantage of the IGCT is the lesser ON-state voltage drop of the device (≈ 3V for a 4.5kV device). The power dissipation for a 1500-kW converter, due to a voltage drop, is 2.4kW per phase (Carrasco et al., 2006) compared to power dissipation 5 kW per phase for an IGBT device.

Although the power capability of the SiC (Silicon Carbide)-based devices are currently inadequate for wind energy integration, the technology is promising for potential wind energy converter configurations made up of paralleled/cascaded power electronic converter cells, where the needs for current and voltage ratings are much lower. The key challenges for SiC devices are their bonding technology, a shortcoming of the stray inductance, slimmer chips as well as higher d*v*/d*t*stress and higher operating temperatures – these limitations must carefully be accounted for in the design and packaging of SiC converter systems (Blaabjerg & Ma, 2013).

CONTROL OF A MODERN WIND POWER SYSTEM

The control of electric power produced from the wind is difficult; if adopted in large quantities, can cause local voltage and frequency fluctuations with severe impact on the quality of power supply. Direct transfer of wind energy to electricity grid can introduce power quality issues owing to the erratic nature and the dynamics of the wind power system. The use of advanced power electronics allows wind generators to function in a variable-speed mode enabling additional wind energy to be captured and controlled (Blaabjerg & Ma, 2013). Power electronic converters must be properly controlled so as to deliver the range of current, voltage, or frequency required for the load as well as to guarantee the needed dynamics. The converter if properly designed can serve as a smooth interface between the load and the grid. In addition, the WECS should provide ancillary services so as to ensure a sustainable wind power conversion.

Some key strategies for reactive power transfer during LVRT operation in WECS are positive and negative sequence control, unity power factor control and constant active/reactive power control (Rodriguez et al., 2007). The control signal maintains a steady reference to the DC link voltage, controlling the amount of energy injected into the grid. The grid-side converter allows wind power transfer to the electric grid. The understanding of grid conditions significantly influences the control techniques. For instance, the discovery of grid faults and the removal of positive and negative sequence currents are essential for controlling the wind power in LVRT operation modes (Blaabjerg, Ma & Yang, 2014b). Grid synchronisation concern plays a vital role as the current transferred into the grid must synchronise with the grid voltage. The second-order generalised integrator-based phase-locked loop gives an improved performance compared to other techniques, particularly for single-phase systems – a good candidate for the synchronisation utilised in industrial applications (Blaabjerg et al., 2006).

The grid side power electronic converter, which carries current at grid frequency helps to maintain a fixed DC link voltage supplying a regulated DC voltage to the machine side converter as well as a normalised voltage and frequency to the utility grid. The timing regulation of the grid-side converter switching can enable variable reactive power output to counter-balance the reactive power drawn from the grid permitting power factor correction. The commonly used technique for controlling the grid-side power electronic converter is Space Vector Pulse Width Modulation (SVPWM). The independent power (active/reactive) control is possible using the SVPWM method and can be utilised in both grid and off-grid applications.

The generator-side converter, which carries current at slip frequency is utilised to supply variable AC voltage and frequency to the rotor winding for optimum control of the speed and the torque of the generator. Among the control techniques available, the field-oriented control is extensively utilised for controlling the generator side while the permanent magnet synchronous generator torque control can be realised by controlling the torque current component of the stator.

CONCLUSION

Wind power generation is growing at an alarming rate due to expeditious growth in global energy demand, rising call for energy sustainability and advances in power electronic technology. Wind energy can be integrated into the grid using power electronics technology, enabling the conversion of electric power from one form to the other, using power semiconductor devices. Power electronics technology enables optimum performance of the WECS, transferring suitable and applicable wind energy into the grid. In order to smoothen the progress of large-scale injection of wind energy into the utility grid in future, more research in the field of power semiconductors is on-going to cater to the emerging demand for power flow control, grid connection standards, communication and protection. Improvements in efficiency of power electronics technology can be achieved by developing more advanced power semiconductor devices with improved reliability, power ratings and lifetime, as well as enhanced control capabilities.

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