Power Electronics Converters for Wind Turbine Systems

Frede Blaabjerg, *Fellow, IEEE*, Marco Liserre, *Senior Member, IEEE*, and Ke Ma, *Member, IEEE*

***Abstract*—The steady growth of installed wind power together with the upscaling of the single wind turbine power capability has pushed the research and development of power converters toward full-scale power conversion, lowered cost pr kW, increased power density, and also the need for higher reliability. In this paper, power converter technologies are reviewed with focus on existing ones and on those that have potential for higher power but which have not been yet adopted due to the important risk associated with the high-power industry. The power converters are classified into single- and multicell topologies, in the latter case with attention to series connection and parallel connection either electrical or magnetic ones (multiphase/windings machines/transformers). It is concluded that as the power level increases in wind turbines, medium-voltage power converters will be a dominant power converter configuration, but continuously cost and reliability are important issues to be addressed.**

***Index Terms*—Multilevel converters, power electronic conversion, renewable energy, semiconductor device reliability, wind energy.**

I. Introduction

WIND turbine system (WTS) technology is still the most promising renewable energy technology. It started in the 1980s with a few tens of kW power production per unit. Today multi-MW size wind turbines are being installed [1]–[4], and they are very advanced power generators. There is a widespread use of WTSs in the distribution networks as well as there are more and more wind power stations which are connected to the transmission networks. Denmark for example has a high-power capacity penetration ($> 30\%$) of wind energy in major areas of the country, and today 25% of all the electrical energy consumption is covered by wind energy. The aim is to achieve a 100% nonfossil-based power generation system in 2050 [5]. Initially, wind power did not have any serious impact on the power system control, but now due to its size, wind power has to play a much more active part in grid operation and control. The technology used in wind turbines was originally based on a squirrel-cage induction generator connected directly to the grid. Power pulsations in the wind were almost directly transferred to the electrical grid by using this technology as the speed is fixed (limited slip range). Furthermore, no dynamic control of the active and reactive power exists except for a few capacitor banks which ensured unity power factor at the point of common coupling. As the power capacity of the wind turbines increases, regulating the frequency and the voltage in the grid become even more important, and in the last decade, it has become necessary to introduce power electronics [6] as an intelligent interface between the wind turbine and the grid. Power electronics is changing the basic characteristic of the wind turbine from being an energy source to being an active power source for the grid. The electrical technology used in the wind turbine is not new. It has been discussed for several decades, but now the cost per kW of new wind power plant is comparable and even lower than coal power plant's one; hence, solutions with power electronics are very attractive [7].

This paper provides an overview of existing power electronics technologies in wind turbines and on those that have the potential for higher power WTSs. In fact, the most recent finding of the Upwind European project are that 20 MW wind turbine is feasible provided some key innovations are developed and integrated [8]. Given the limited technical literature details about power converter configuration in industrial products, the paper aims at classifying the solutions proposed in scientific literature but which have not been presented in a comprehensive way. First, the basic market developments are discussed with a focus on cost, size, and power density, also in respect to the adopted generator technology, to the filter and transformer, and to the switching devices used. Next, wind conversion is discussed with attention on two competing philosophies—one with reduced power converter which has been popular up to now—a second with a full-scale power converter which is becoming more and more the preferred choice. The most promising power converter topologies for wind turbines are further presented and compared by classifying them into single-cell and multicell structure. Reliability issues are also discussed in this context as they become more and more important.

II. Wind Turbine Systems

Wind power has until now grown to a cumulative worldwide installation level of 200 GW with close to 40-GW installed alone in 2010, according to BTM Consult, indicating that wind power is really an important player in some areas of the

Manuscript received July 5, 2011; revised November 25, 2011; accepted November 28, 2011. Date of publication December 23, 2011; date of current version March 21, 2012. Paper 2011-IPCC-385.R1, presented at the 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, September 17–22, and approved for publication in the IEEE Transactions on Industry Applications by the Industrial Power Converter Committee of the IEEE Industry Applications Society.

F. Blaabjerg and K. Ma are with the Department of Energy Technology, Aalborg University, DK-9220 Aalborg East, Denmark (e-mail: fbl@et.aau.dk; kema@et.aau.dk).

M. Liserre is with the Department of Electrotechnical and Electronic Engineering, Polytechnic of Bari, 70125 Bari, Italy (e-mail: liserre@poliba.it).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2011.2181290

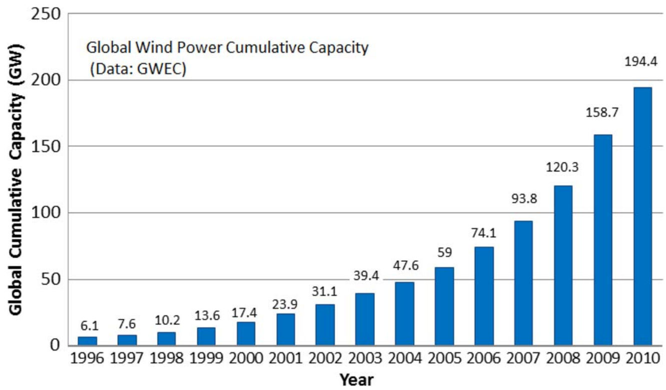


Fig. 1. Annual global cumulative installed wind power capacity from 1996 to 2010 (Source: GWEC).

world [9]. The worldwide penetration of wind power electricity was 1.8%, and the prediction for 2019 is more than 8% or 1 TW cumulative installations. China was the largest market in 2010, and in general the EU, the USA, and China are sharing around one third of the total market. The global accumulated installed power capacity is shown in Fig. 1.

In 2010, the Danish company Vestas Wind Systems A/S was still in the top position among the largest manufacturers of wind turbines in the world, closely followed by the Chinese company Sinovel as the second largest in the world. This company was third in 2009, and this data gives some idea of the impressive interest in Asia for wind energy. Fig. 2 shows the wind turbine top suppliers in 2010, also published by BTM Consult.

A. Generators in Wind Turbine Systems

Synchronous generators, either externally excited or with permanent magnets, are becoming the preferred technology in the best seller power range [1]–[4]. Multipole permanent magnet synchronous generator (PMSG) with a full power back-to-back converter looks to become the most adopted generator in the near future due to the reduced losses and lower weight if compared to the externally excited SG that is manufactured successfully by, e.g., the German company Enercon. In the last case, the generator is an anular generator, and rotor current is used to regulate the dc link voltage. The transition seems mainly to be valid for larger wind turbines (3–6 MW). However, the increased prices of rare-earth magnets might change the philosophy of wind turbine drive trains to avoid high risk in expenses.

B. Power Electronics Converters in Wind Turbine Systems

The penetration of power electronics in WTSs has been continuously growing since the 1980s, when it consisted of a thyristor-based soft starter just for initially interconnecting the wind turbine and after that being by-passed and the generator was operating directly to the grid. In the 1990s, it was mainly the use of rotor resistance control with a diode bridge and a power electronic switch; finally, the back-to-back power converter emerged, first in reduced power for doubly fed induction generator (DFIG), then in full power [2], [3], [6]. Fig. 3 shows the evolution of WTS size and the use of power electronics capacity highlighted with an inner circle in blue. The most adopted solution in power converters for WTSs in the best seller range 1.5–3 MW is the use of two two-level voltage source converters in a back-to-back configuration [1]. At lower and higher powers, it is possible to find other solutions such as a diode bridge for the generator in the case of a synchronous generator and also the use of multilevel converters to enter medium voltage for high-power applications.

The demands posed on power electronic converters for WTSs are shown in Fig. 4.

As the interface between the wind turbine generator and power grid, the wind power converter has to satisfy the requirements to both sides. For the generator side: the current flowing in the generator stator should be controlled to adjust torque and as a consequence the rotating speed. This will contribute to the active power balance in normal operation when extracting the maximum power from the wind turbine but also in case grid faults appear [4]. Moreover, the converter should have the ability to handle variable fundamental frequency and voltage amplitude of the generator output to control the speed.

For the grid side: the converter must comply with the grid codes regardless of the wind speed. This means it should have the ability to control the inductive/capacitive reactive power Q, and perform a fast active power P response. The fundamental frequency as well as voltage amplitude on the grid side should be almost fixed under normal operation, and the total harmonic distortion (THD) of the current must be maintained at a low level [6], [10], [11].

Inherently, the converter needs to satisfy both the generator side and grid side requirements with a cost-effective and easy maintenance solution. This requires a high-power density, reliability, and modularity of the entire converter system. Moreover, the wind power converter may need the ability to store the active power and boost up the voltage from the generator side to the grid side [1].

C. Transformers and Filters in Wind Turbine Systems

Transformers and filters have a pivotal role for volume and losses. All wind turbine manufacturers are using a step-up transformer for connecting the generator to the grid. Research is ongoing in order to replace it with a transformer with a unity transformer ratio or even maybe to avoid it—leading to high-power and high-voltage transformerless solutions [12] which is a technological challenge. Regarding filters, typically an LCL filter is the adopted solution to attenuate PWM harmonics [13], but in case a diode bridge is adopted on the generator side and in case of higher power WTS that have also strict demands to grid voltage harmonics, trap filters might also be adopted in the final solution. Damping of resonances, associated to the LCL filter, is important also and the use of passive damping can create high losses (and thereby lower energy production) and compromise the attenuation of PWM harmonics provided by the filter. This may lead to the use of active damping, acting on the controller structure or to use more complex passive damping solutions [14].

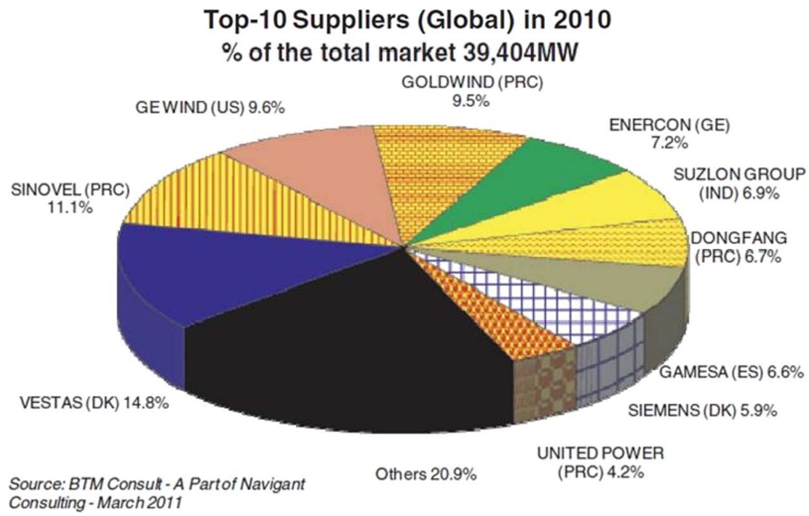


Fig. 2. Wind turbine market share distributed by manufacturers in 2010. (Source: BTM Consult).

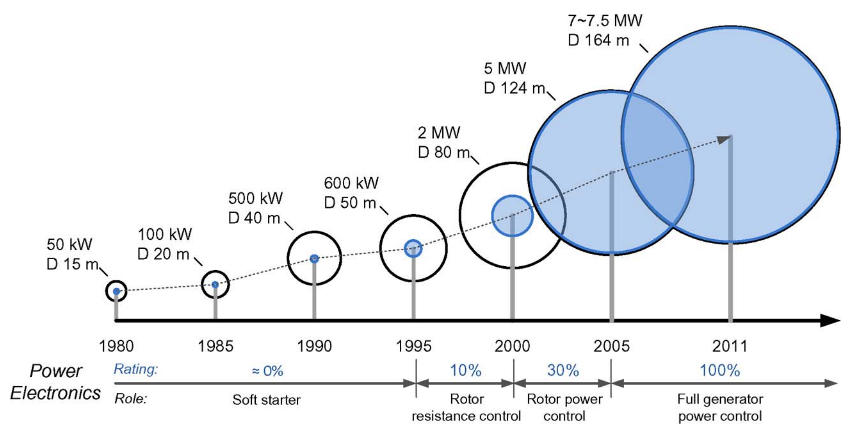


Fig. 3. Wind turbine evolution and the main trend of power electronic conversion (blue indicates power level of converters) in the last 30 years.

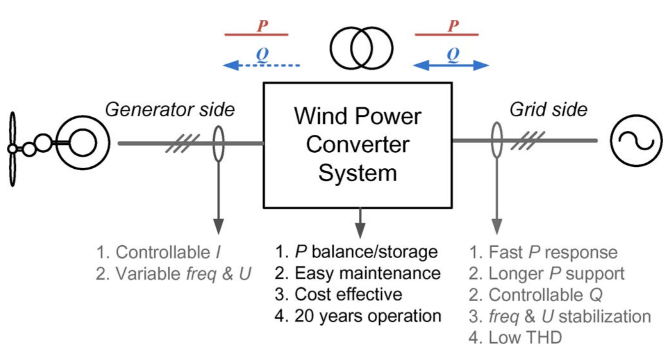


Fig. 4. Wind power conversion and demands to power electronics.

D. Switching Devices

The latest development in switching devices is playing an important role in the development of higher power converters for wind turbines with increased reliability and efficiency. The main choices are IGBT modules, IGBT press pack, and IGCT press pack as shown in Table I.

The press-pack technology leads to an increase in reliability, yet to be scientifically proven but known from industrial experience, higher power density (easier stacking for series connection), and better cooling capability at the price of a higher cost compared to power modules. Press-pack IGCT supports the development of MV converters and are already state of the art in high-power electric drives (e.g., for oil and gas application) but not yet widely adopted in the wind turbine industry also because of cost issues [15]–[17].

However, the module technology has longer record of applications and less mounting problems. Moreover, the most critical point for reliability, the lift-off—due to thermal cycling—of the bond wires used to connect the dies in the module [15], is an area of ongoing improvements both in materials [18] and solution (use of flexible foils instead of bond wires leading to 35% reduction in volume [19]).

III. Wind Turbine Concepts

As shown in Fig. 3, more and more power electronics have been incorporated into WTSs to improve wind turbine control and to improve the interconnection to the grid system. In this paper, focus is primarily on the systems where complete control of active and reactive power can be obtained in all

TABLE I
MAIN SWITCHING DEVICES FOR WIND POWER CONVERTERS

	IGBT module	IGBT Press-pack	IGCT Press-pack
Power Density	Moderate	High	High
Reliability	Moderate	High	High
Cost	Moderate	High	High
Failure mode	Open circuit	Short circuit	Short circuit
Easy maintenance	+	-	-
Insulation of heat sink	+	-	-
Snubber requirement	-	-	+
Thermal resistance	Moderate	Small	Small
Switching loss	Low	Low	High
Conduction loss	High	High	Low
Gate driver	Small	Small	Large
Major manufacturers	Infineon, Mitsubishi ABB, Semikron, Fuji	Westcode, ABB	ABB
Medium voltage ratings	3.3 kV / 4.5 kV / 6.5kV	2.5 kV / 4.5 kV	4.5 kV / 6.5 kV
Max. current ratings	1.5 kV / 1.2 kA / 750 A	2.2 kA / 2.4 kA	2.1 kA / 1.3 kA

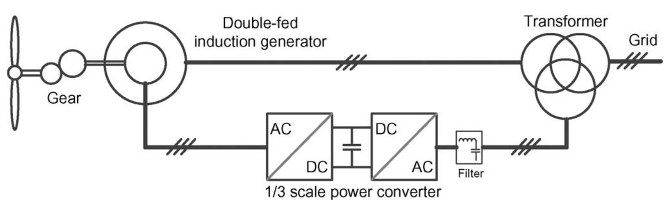


Fig. 5. Variable speed wind turbine with partial-scale power converter.

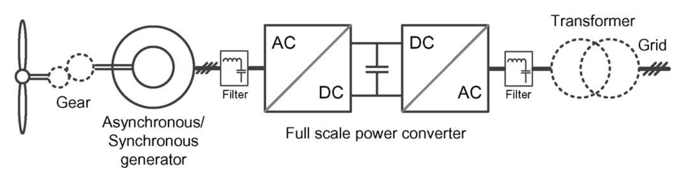


Fig. 6 Variable speed wind turbine with full-scale power converter.

operating points by using partial-scale power converter or full-scale power converter.

A. Variable Speed WT With Partial-Scale Power Converter

The most adopted partial scale frequency converter is adopted in conjunction with the DFIG concept, which gives a variable speed controlled wind turbine with a wound rotor induction generator and partial scale power converter (rated to approximately 30% of nominal generator power) on the rotor circuit. The topology is shown in Fig. 5.

The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed. The power rating of this partial-scale frequency converter defines the speed range (typically $\pm 30\%$ around synchronous speed). Moreover, this converter performs reactive power compensation and a smooth grid interconnection. The smaller frequency converter makes this concept attractive from an economical point of view. In this case, the power electronics is enabling the wind turbine to act as a dynamic power source to the grid. However, its main drawbacks are the use of slip rings and the protection schemes/controllability in the case of grid faults [20], [21].

The use of a reduced size converter is also feasible with PMSG as, e.g., proposed in [22] where a 20% power converter is placed in series with the stator winding to actively damp the generator.

B. Variable Speed Wind Turbine With Full-Scale Power Converter

A variable speed wind turbine configuration with full-scale power conversion corresponds to the full variable speed controlled wind turbine, with the generator connected to the grid through a power converter as shown in Fig. 6.

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

Some variable speed WTSs are gearless—see dotted gearbox in Fig. 6. In these cases, a heavier direct driven multipole generator is used. The wind turbine companies Enercon and Siemens Wind Power are examples of manufacturers who are using more direct driven type systems. The voltage level of the full-scale power conversion can be from low-voltage (below 1 kV) to medium-voltage (MV) level and, in the future, the voltage level might be appropriate to connect more directly to the grid system and to avoid the transformer [12].

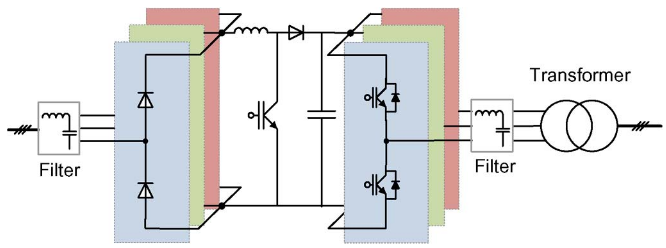


Fig. 7. Full-rated power converter wind turbine with permanent magnet generator.

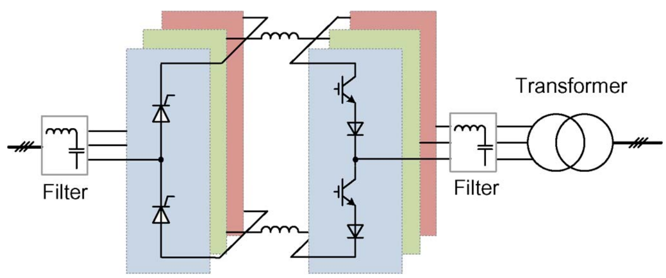


Fig. 8. Full-rated power converter wind turbine with permanent magnet generator (Current source version).

IV. Single-Cell Power Converters for Wind Turbines

A. Unidirectional Power Converter Solutions

Today, it is a trend to use a PMSG in the full-rated power converter wind turbine. As there is no reactive power needed in such a generator and active power flows unidirectionally from the PMSG to the grid through a power converter, only a simple diode rectifier can be applied to the generator side converter in order to obtain a cost-efficient solution. However, diode rectifier even if multiphase or 12-pulses introduces low-frequency pulsations that can trigger shaft resonance [24]. Semicontrolled rectifier solutions are also possible [25].

In order to get variable speed operation and stable dc bus voltage, a boost dc-dc converter could be inserted in the dc link or dc voltage can be controlled using rotor excitation, as shown in Fig. 7. It should be mentioned that for power levels in the range of MWs, the dc/dc converter needs to be made by several interleaved units or by a three-level solution [23].

Fig. 8 shows the use of two current source converters in a back-to-back connection [26]. The advantage of the proposed solution can be to exploit the inductance of the long cables used in wind parks if a dc distribution is adopted or used in the case of the generator converter is placed in the nacelle while the grid converter is placed at the bottom of the WTS [27]. The use of a voltage source inverter on the grid side is mandatory in case of Fig. 7 topology since capacitive dc storage is used. In a similar way, the use of current source inverter on the grid side is mandatory in the case of Fig. 8 topology is used since the dc storage is inductive.

B. Two-Level Power Converter (2L-BTB)

Pulse width modulation-voltage source converter with two-level output voltage (2L-PWM-VSC) is the most frequently used three-phase power converter topology so far in wind turbines systems. The knowledge available in this field is extensive, and it is a well-established technology. As the interface between the generator and grid in the WTS, two 2L-PWM-VSCs are usually configured as a back-to-back structure (2L-BTB) with a transformer on the grid side, as shown in Fig. 9. A technical advantage of the 2L-BTB solution is the relatively simple structure and few components, which contributes to a well-proven robust and reliable performance.

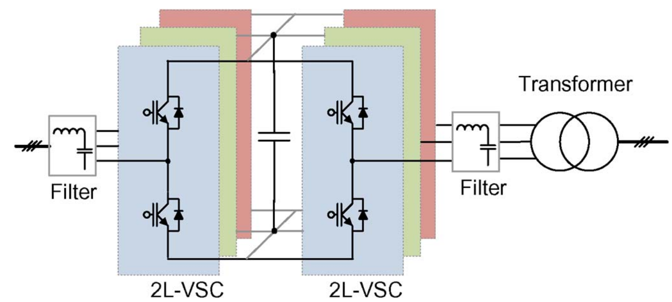


Fig. 9. Two-level back-to-back voltage source converter for wind turbines. (2L-BTB).

However, as the power and voltage range of the wind turbine are increasing, the 2L-BTB converter may suffer from larger switching losses and lower efficiency at megawatts (MW) and MV power levels. The available switching devices also need to be paralleled or connected in series in order to obtain the required power and voltage of wind turbines, which may lead to reduced simplicity and reliability of the power converter [28].

Another problem in the 2L-BTB solution is the two-level output voltage. The only two voltage stages introduce relatively higher dv/dt stresses to the generator and transformer. Bulky output filters may be needed to limit the voltage gradient and reduce the THD [29].

The 2L-BTB topology is state of the art in DFIG-based wind turbines, e.g., [2], [3], [30]. Several manufacturers are also using this topology for full-rated power converter wind turbines with a squirrel-cage induction generator.

C. Multilevel Power Converter

As mentioned above, power capacity of wind turbines keeps climbing up (even to 10 MW), and it becomes more and more difficult for a traditional 2L-BTB solution to achieve acceptable performance with the available switching devices. With the abilities of more output voltage levels, higher voltage amplitude and larger output power, multilevel converter topologies are becoming interesting and popular candidates in the wind turbines application [31]–[33].

Generally, multilevel converters can be classified into three categories [33, 35, 36]: neutral-point diode clamped structure, flying capacitor clamped structure, and cascaded converter cells structure. In order to get a cost-effective design, multilevel converters are mainly used in the 3 MW to 7 MW variable-speed full-scale power converter wind turbines. Several possible multilevel solutions are presented in the following.

1) Three-Level Neutral-Point Diode Clamped Back-To-Back Topology (3L-NPC BTB): Three-level neutral-point diode

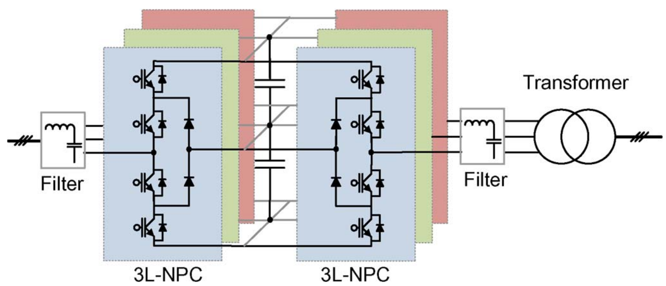


Fig. 10. Three-level neutral-point clamped back-to-back converter for wind turbines. (3L-NPC BTB).

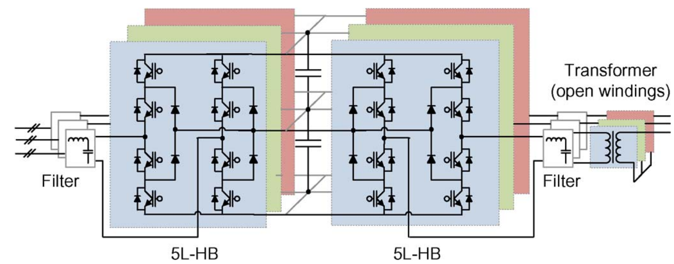


Fig. 12. Five-level H-bridge back-to-back converter for wind turbines. (5L-HB BTB).

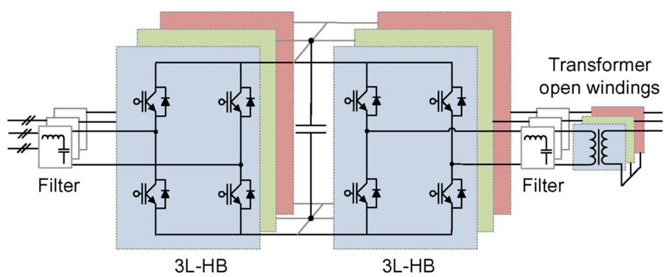


Fig. 11. Three-level H-bridge back-to-back converter for wind turbines. (3L-HB BTB).

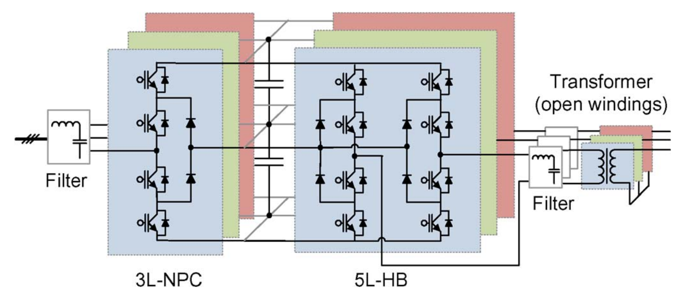


Fig. 13. Three-level neutral-point clamped and five-level H-bridge converter for wind turbines. (3L-NPC + 5L-HB).

clamped topology is one of the most commercialized multilevel converters on the market. Similar to the 2L-BTB, it is usually configured as a back-to-back structure in wind turbines, as shown in Fig. 10, which is called 3L-NPC BTB for convenience.

It achieves one more output voltage level and less dv/dt stress compared to the 2L-BTB, thus the filter size is smaller. The 3L-NPC BTB is also able to output the double voltage amplitude compared to the two-level topology by the switching devices of the same voltage rating. The midpoint voltage fluctuation of dc bus used to be a drawback of the 3L-NPC BTB. However, this problem has been extensively researched and is considered improved by the controlling of redundant switching status [36]. However, it is found that the loss distribution is unequal between the outer and inner switching devices in a switching arm, and this problem might lead to derated converter power capacity when it is practically designed [32], [36], [37].

2) Three-Level H-Bridge Back-to-Back Topology (3L-HB BTB): The 3L-HB BTB solution is composed of two H-bridge converters which are configured in a back-to-back structure, as shown in Fig. 11. It can achieve output performance similar to the 3L-NPC BTB solution, but the unequal loss distribution and clamped diodes are eliminated. More efficient and equal usage of switching devices as well as higher designed power capacity might be obtained [31], [32], [38].

Moreover, as only half of the dc bus voltage is needed in 3L-HB BTB compared to the 3L-NPC BTB, there are less series connection of capacitors and no midpoint in dc bus, thus the size of dc link capacitors can be further reduced.

However, a 3L-HB BTB solution needs an open-winding structure in the generator and transformer in order to achieve isolation between each phase. This feature has both advantages and disadvantages: on one hand, an open-winding structure enables relatively isolated operation of each phase, and a potential fault-tolerant ability is thereby obtained if one or even two phases of the generator or the generator side converter are out of operation. On the other hand, an open-winding structure requires double cable length and weight in order to connect with the generator and the transformer. Extra cost, loss, and inductance in the cables can also be major drawbacks. The open-winding impacts on the loss/weight of the generator and the transformer still need to be further investigated.

3) Five-Level H-Bridge Back-to-Back Topology (5L-HB BTB): The 5L-HB BTB converter is composed of two back-to-back H-bridge converters making use of 3L-NPC switching arms, as shown in Fig. 12. It is an extension of 3L-HB BTB and shares the same special requirements for the open-winding generator and transformer.

With the same voltage rating of the switching devices, 5L-HB BTB can achieve five level output voltage, and double voltage amplitude compared to the 3L-HB BTB solution. These features enable smaller output filter and less current rating in the switching devices as well as in the cables [29], [39].

However, compared to 3L-HB BTB, the 5L-HB BTB converter introduces more switching devices, which could reduce the reliability of the total system. The problems of unequal loss distribution as well as larger dc link capacitors will unfortunately also return.

4) Three-Level Neutral-Point Diode Clamped Topology for Generator Side and Five-Level H-Bridge Topology for Grid Side (3L-NPC + 5L-HB): Generally, the output quality requirements of the grid side are much stricter than those of the generator side [40]. To adapt this unsymmetrical requirement for wind power converters, a “compound” configuration employing 3L-NPC topology on the generator side and 5L-HB topology on the grid side can be adopted, as shown in Fig. 13.

TABLE II
COMPARISON OF THE ONE-CELL POWER CONVERTER SOLUTIONS FOR WIND TURBINES

	3L-NPC	3L-HB	5L-HB	3L + 5L
IGBT numbers	24	24	48	36
Diode numbers [1]	36	24	72	54
Switch current	I_{ph}	I_{ph}	I_{ph}	I_{ph}
Switch voltage	$0.5V_{dc}$	V_{dc}	$0.5V_{dc}$	$0.5V_{dc}$
Max. output voltage [2]	$0.5V_{dc}$	V_{dc}	V_{dc}	$0.5V_{dc} + V_{dc}$
Output-Switch voltage ratio	1	1	2	1 + 2
Voltage WTHD [3]	0.84 %	1.15 %	0.73 %	0.73%
Output connection	Standard	Open winding	Open winding	Open winding
Fault tolerant ability [4]	No	Yes	Yes	No
Advantages	Matured technology	Less DC link capacitors, Equal loss distribution	More output voltage levels, Higher voltage utilization of device [5]	Higher performances on grid side than generator side
Disadvantages	Unequal loss distribution, DC bus midpoint	Zero-sequence current path, More cables	Zero-sequence current path, More cables and devices	Unequal loss distribution, DC bus midpoint

Notes:
1. Include both freewheeling diodes and clamping diodes. 2. Theoretical maximum amplitude of output phase voltage.
3. Simulation results of grid inverter, f_s/f_o=21, M=1, 80th harmonics, modulation methods in [56], voltage of V_a-V_b.
4. If one or two phase of generator side converter fails, still keep working.
5. Larger output-switch voltage ratio (higher output voltage using the same voltage rating devices).

On the generator side, this configuration has a performance similar to the 3L-NPC BTB solution. While on the grid side, it has the same performance to 5L-HB BTB. The voltage levels and amplitude of the grid side are higher than those on the generator side. It is noted that an open-winding structure in the generator is avoided; the cable length on the generator side is therefore reduced to half, but the potential fault-tolerant ability is also eliminated. It has less switching devices compared to 5L-HB BTB, but still unequal loss distribution in the switching devices exists.

In all the previously proposed solutions, the large amount of power semiconductors as well as auxiliary components could reduce the converter reliability and increase the cost. The total system weight and volume reduction in the wind turbine application still needs to be further investigated.

The comparisons between the five solutions for single-cell full-scale power converter wind turbines are shown in Table II, regarding power semiconductor numbers, the output voltage ability, fault-tolerant ability, as well as major advantages and disadvantages.

V. MULTIPLE CELLS POWER CONVERTERS FOR WIND TURBINES

Up till now, one of the most commercialized cascaded converter cells multilevel topologies is the cascaded H-bridge (CHB) converter as shown in Fig. 14. Unfortunately, the CHB needs an isolated dc link for each converter cell. This characteristic may involve a complex multipulse transformer on the generator side, resulting in larger weight and volume [29], [41].

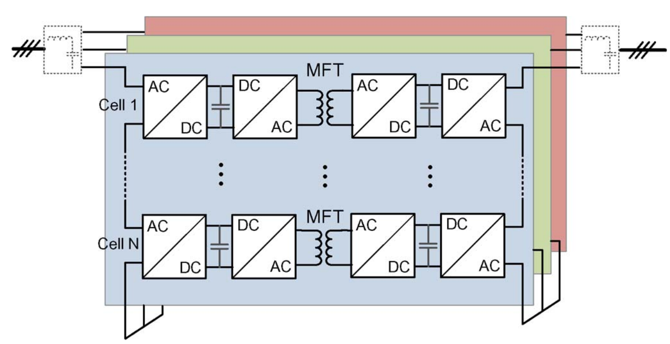


Fig. 14. Cascaded H-bridge back-to back converter for wind turbines with medium-frequency transformer ($\boldsymbol{S}-\boldsymbol{S}$).

A configuration which shares a similar idea with some of the next generation traction converters [42], [43], as well as the European UNIFLEX-PM Project [44] is proposed in Fig. 14. It is based on a back-to-back CHB converter structure, with galvanic insulated dc/dc converters as interface. The dc/dc converters with medium-frequency transformer operate at several

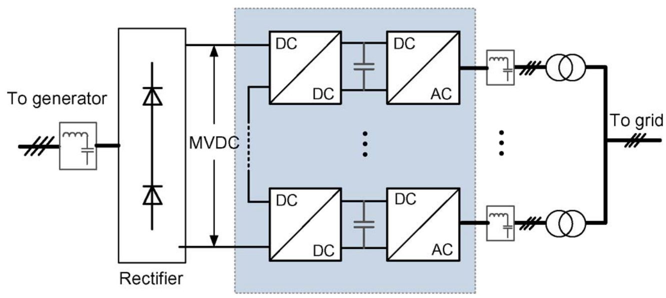


Fig. 15. Series connection of power converter cells using a common grid converter diode bridge, an MVDC link, and boost converters with two-level inverters parallel connected to the grid ($\boldsymbol{S}-\boldsymbol{P}$).

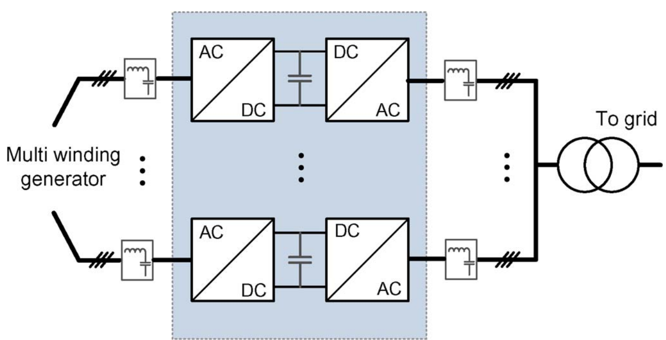


Fig. 16. Parallel connection of power converters in which PWM signals are interleaved to achieve harmonic cancellation ($\boldsymbol{P}-\boldsymbol{P}$).

kHz to dozens of kHz, the transformer size is thereby reduced. Because of the cascaded structure, this configuration can be directly connected to the transmission power grid (10 kV–20 kV) with high output voltage quality, filterless design, and redundancy ability [42]–[44].

Fig. 15 shows a different approach, prosed by Semikron, to increase the power by using a multicell structure, i.e., the connection of them in series on a MVDC bus, while the grid converters are connected in parallel [45]. The main advantage is that standard low voltage modules may be used for a MVDC application.

Fig. 16 shows the solution adopted by Gamesa in the 4.5-MW wind turbine [46] with parallel connection of cells both on the generator side and on the grid side. Siemens also introduce this kind of solution in some of their multi-MW wind turbines [47].

Fig. 17 shows a solution for a high-power high-voltage transformerless WTS where the coils of the generator are connected to the ac/ac converter that are connected in series on the grid side. The coil windings need to be isolated [12].

Fig. 18 shows a power converter obtained with series connection of matrix converters in which the output feed several windings of a transformer leading to a magnetic parallel configuration [48].

All the reviewed topologies have fault-tolerant capabilities, and all of them are also using a higher number of components. The main differences are in the requirement they have in respect to the generator and in respect to the transformer as outlined in Table III.

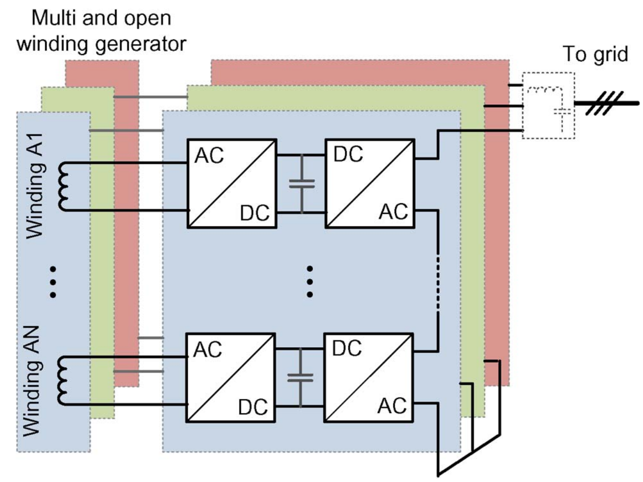


Fig. 17. Magnetic parallel connection of power converters on the generator side and series connection on the grid side ($\boldsymbol{MP}-\boldsymbol{S}$).

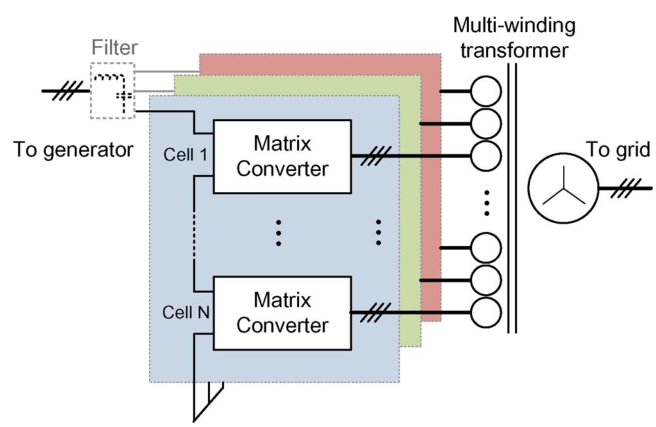


Fig. 18. Series connection of matrix converters with magnetic paralleling on the grid side ($\boldsymbol{S}-\boldsymbol{MP}$).

TABLE III
COMPARISONS OF THE MULTICELL SOLUTIONS FOR WIND TURBINES

Configurations	***S-S***	***S-P***	***P-P***	***S-MP***	***MP-S***
Generator	Standard	Standard	Open winding	Standard	Open winding
Transformer	0	- -	-	- - -	0

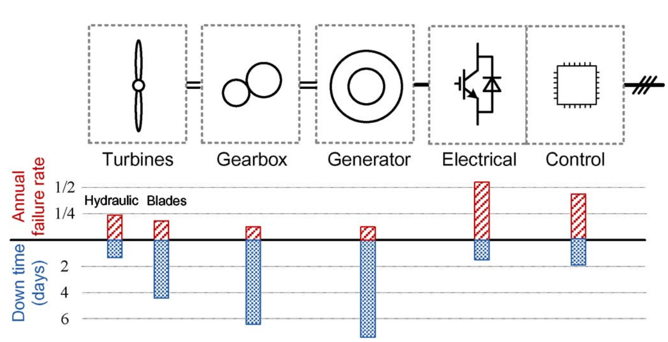


Fig. 19. Wind turbine overview in respect to reliability where registered annual failure rate and down time are illustrated. Data from [50].

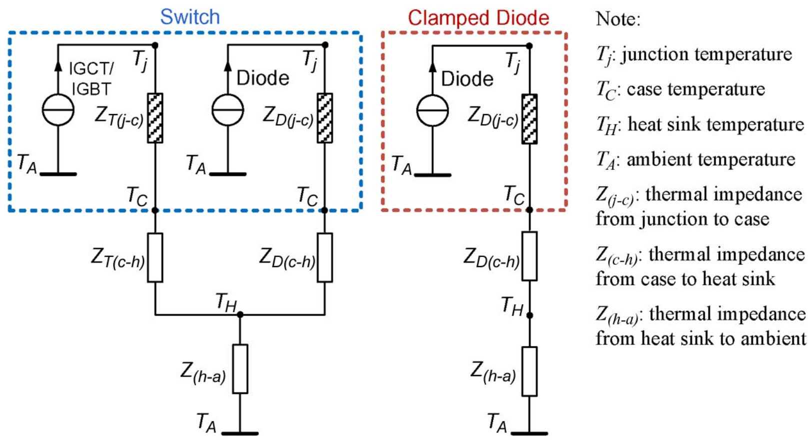


Fig. 20. Example of thermal models of the power devices in a power converter.

VI. Reliability Issues

The penetration of wind power into the power grid is fast growing even expected to be 20% of the total electricity production at 2020 in Europe [49]. Meanwhile, the power capacity of a single wind turbine is increasing continuously in order to reduce the price pr. produced kWh, and the location of wind farms is moving from onshore to offshore because of land limits and more wind energy production in the offshore. Consequently, due to much more significant impacts to the power grid, as well as higher cost to maintain and repair after failures than ever before, the wind power generation system is required to be more reliable and able to withstand some extreme grid or environment disturbances. Reliability is one of the key issues that concerns WTS manufacturers and investors in order to ensure high-power security (availability). Market feedback has shown that the control and power converters seem to be more prone to failure even though the generator and gearbox have the largest downtime, as shown in Fig. 19 [50]. The need for higher power density in power converters, as already outlined, leads to more compact design, reduced material use, and equipment cost [51]. All may invoke new failure mechanisms in the power and control electronics. Exposure to moisture, vibration, dust, chemicals, high voltage, and temperature is predominant in WTSs failure drivers.

The study of reliability in power electronics is moving from a statistically based approach that has been proven to be unsatisfactory in achieving higher safety levels in the automotive industry, where the standards are very high, to a physics-of-failure approach which involves the study of each of the phenomena that lead to failures of power electronics [52], [53] and also the entire wind turbine.

The main driver of the semiconductor failures has been found to be the thermal cycling of the different materials, with different expansion coefficients, which stress the power switches. The thermal cycling appears when power semiconductors in the converter commute unevenly and periodically. The thermal chain as shown in Fig. 20 determines a periodical thermal excursion of the different materials, which expand and compress until different failure mechanism are triggered. Different power switches are based on different technologies, e.g., module integrated or press pack, and on different characteristics leading to a number of possible combinations of failure mechanisms.

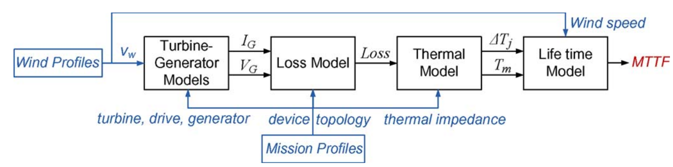


Fig. 21. From the definition of a mission profile to a reliability model of a power converter in a wind turbine.

Hence, it is important that a clear mission profile exist, including the definition of all the stresses to which the semiconductors are subjected, before the power converter reliability is evaluated as shown in Fig. 21.

Through analysis, understanding and modeling of failure mechanisms and field load, the goal of seeking correlations between electrical measurements on failed components and the observed failure, need to be pursued. This will lead to the development of real-time monitoring and prediction that consists of identifying methods for the real-time (online) detection of the lifetime (wear-out) state of the power transistor (or power diode) by monitoring various relevant (thermal, electrical, optical, etc.) sensor signals [54]. For example, the collector-emitter voltage VCE of an IGBT, which is subject to an accelerated test, experiences a sudden increase just before the IGBT failure [55] and can be used for predictive maintenance in the WTS.

Moreover, a new interesting area of research is the use of modulation and control optimized to reduce the maximum junction temperature (Fig. 22) or the maximum junction temperature fluctuation (Fig. 23) under particularly stressing conditions such as low voltage ride through [56] or wind gusts [57].

The zero voltage level output of 3L-NPC inverter introduces losses to the clamping diode D_{npc}, which will be more stressed during the low voltage ride through operation of power grid. The basic idea of the thermal optimized modulation O1 and O2 is trying to reduce the duration time of zero voltage level by utilizing the switching state redundancy in the inner hexagonal of space vector diagram of three-level NPC inverter. By the same time, the control ability of dc bus midpoint potential is still maintained.

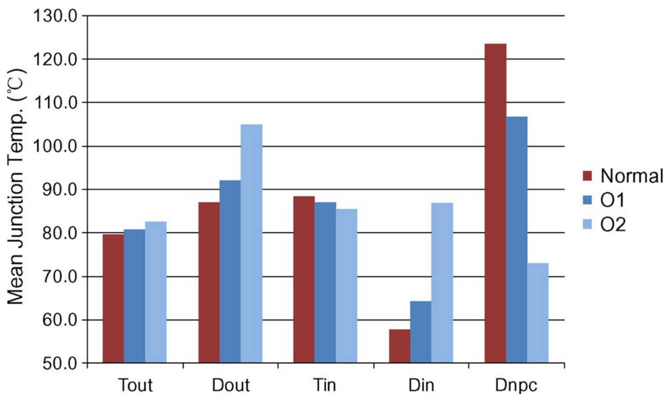


Fig. 22. Mean junction temperature considering normal and optimized modulation sequences for the 3L-NPC wind power inverter under LVRT. Vg = 0.05 p.u. 100% reactive current.

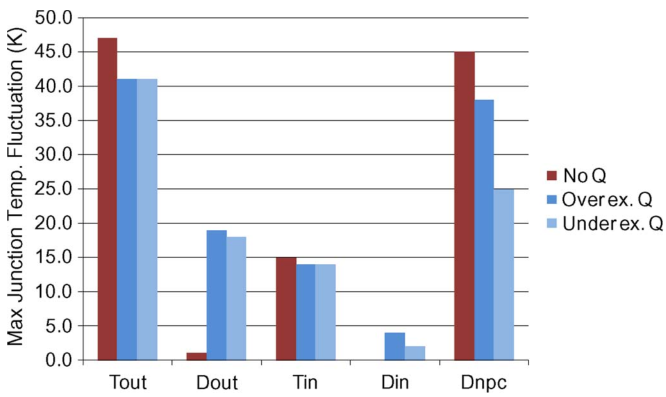


Fig. 23. Maximium thermal fluctuation of 3L-NPC inverter with different reactive powers (Considering parallel converters).

During wind gust, the junction temperature fluctuation in the power devices of wind power converter may be serious. The basic idea of this method is to circulate the reactive power among paralleled converters in a wind farm to somehow stabilize the temperature fluctuation, by the same time the reactive power regulations by the power grid standards are still satisfied.

VII. Conclusion

The paper has given an overview of different power electronic converters in WTSs with special attention paid to the many possible topologies at low voltage and medium voltage. An important trend is that the technology is moving toward a higher power level, and it is inevitable that it goes for higher voltage and as a consequence into multilevel single-cell structures or to multicell modular structures that can even use standard low voltage power converter modules. One current concern beyond being able to upscale the power is being better able to predict reliability of power electronic converters and control, as it has been a major failure cause in WTS, and better lifetime prediction and condition monitoring methods in the future will be important to improve the technology. The use of a multicell approach in the power converter design can also lead to transformerless high-power converters which are directly connected to a MV grid with reduction of power losses, weight, and volume. Research is ongoing in this direction. Further, as the wind turbines are aggregated into wind power stations—configurations most useful for single-turbine operation are perhaps not the most feasible solution for a large-scale off-shore wind farm needing a large power transmission system.

References

[1] M. Liserre, R. Cardenas, M. Molinas, and J. Rodriguez, "Overview of multi-MW wind turbines and wind parks," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1081–1095, Apr. 2011.

[2] Z. Chen, J. M. Guerrero, and F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines," *IEEE Trans. Power Electron.*, vol. 24, no. 8, pp. 1859–1875, Aug. 2009.

[3] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

[4] A. D. Hansen, F. Iov, F. Blaabjerg, and L. H. Hansen, "Review of contemporary wind turbine concepts and their market penetration," *J. Wind Eng.*, vol. 28, no. 3, pp. 247–263, 2004.

[5] *Green Energy—The Road to a Danish Energy System Without Fossil Fuels*, Danish Comm. Climate Change Policy, Copenhagen, Denmark. [Online]. Available: http://www.klimakommissionen.dk/en-US/

[6] M. P. Kazmierkowski, R. Krishnan, and F. Blaabjerg, *Control in Power Electronics-Selected Problems*. New York: Academic, 2002.

[7] M. Milligan, K. Porter, E. DeMeo, P. Denholm, H. Holttinen, B. Kirby, N. Miller, A. Mills, M. O'Malley, M. Schuerger, and L. Soder, "Wind power myths debunked," *IEEE Power Energy Mag.*, vol. 7, no. 6, pp. 89–99, Nov./Dec. 2009.

[8] *Design Limits and Solutions for Very Large Wind Turbines*, Mar. 2011. UpWind project. [Online]. Available: http://www.ewea.org/fileadmin/ewea_documents/documents/upwind/21895_UpWind_Report_low_web.pdf

[9] Website of BTM Consult, Denmark. [Online]. Available: http://www.btm.dk/

[10] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[11] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*. Hoboken, NJ: IEEE/Wiley, 2011.

[12] C. H. Ng, M. A. Parker, L. Ran, P. J. Tavner, J. R. Bumby, and E. Spooner, "A multilevel modular converter for a large, light weight wind turbine generator," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1062–1074, May 2008.

[13] M. Liserre, F. Blaabjerg, and S. Hansen, "Design and control of an LCL-filter-based three-phase active rectifier," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1281–1291, Sep./Oct. 2005.

[14] A. Rockhill, M. Liserre, R. Teodorescu, and P. Rodriguez, "Grid filter design for a multi-megawatt medium-voltage voltage source inverter," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1205–1217, Apr. 2011.

[15] C. Busca, R. Teodorescu, F. Blaabjerg, S. Munk-Nielsen, L. Helle, T. Abeyasekera, and P. Rodriguez, "An overview of the reliability prediction related aspects of high power IGBTs in wind power applications," *Microelectron. Reliab.*, vol. 51, no. 9–11, pp. 1903–1907, Sep.–Nov. 2011.

[16] R. Jakob, C. Keller, and B. Gollentz, "3-Level high power converter with press pack IGBT," in *Proc. EPE*, Sep. 2–5, 2007, pp. 1–7.

[17] R. Alvarez, F. Filsecker, and S. Bernet, "Comparison of press-pack IGBT at hard switching and clamp operation for medium voltage converters," in *Proc. EPE 2011*, 2011, pp. 1–7.

[18] Website of heraeus. [Online]. Available: http://www.heraeus.com/

[19] Website of Semikron. [Online]. Available: http://www.semikron.com/

[20] S. Muller, M. Deicke, and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines," *IEEE Ind. Appl. Mag.*, vol. 8, no. 3, pp. 26–33, May/Jun. 2002.

[21] D. Xiang, L. Ran, P. J. Tavner, and S. Yang, "Control of a doubly fed induction generator in a wind turbine during grid fault ride-through," *IEEE Trans. Energy Convers.*, vol. 21, no. 3, pp. 652–662, Sep. 2006.

[22] S. Grabic, N. Celanovic, and V. A. Katic, "Permanent magnet synchronous generator cascade for wind turbine application," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1136–1142, May 2008.

[23] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion and Control of Wind Energy Systems*. Hoboken, NJ: Wiley, 2011.

[24] A. Faulstich, J. K. Stinke, and F. Wittwer, "Medium voltage converter for permanent magnet wind power generators up to 5 MW," in *Proc. EPE*, 2005, pp. 1–9.

[25] D. S. Oliveira, M. M. Reis, C. Silva, L. B. Colado, F. Antunes, and B. L. Soares, "A three-phase high-frequency semicontrolled rectifier for PM WECS," *IEEE Trans. Power Electron.*, vol. 25, no. 3, pp. 677–685, Mar. 2010.

[26] J. Dai, D. D. Xu, and B. Wu, "A novel control scheme for current-source-converter-based PMSG wind energy conversion systems," *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 963–972, Apr. 2009.

[27] P. Tenca, A. A. Rockhill, T. A. Lipo, and P. Tricoli, "Current source topology for wind turbines with decreased mains current harmonics, further reducible via functional minimization," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1143–1155, May 2008.

[28] J. Rodriguez, S. Bernet, W. Bin, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2930–2945, Dec. 2007.

[29] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B. Wu, J. Rodriguez, M. A. Perez, and J. I. Leon, "Recent advances and industrial applications of multilevel converters," *IEEE Trans. Power Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010.

[30] R. Pena, J. C. Clare, and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable speed wind-energy generation," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 143, no. 3, pp. 231–241, May 1996.

[31] K. Ma, F. Blaabjerg, and D. Xu, "Power devices loading in multilevel converters for 10 MW wind turbines," in *Proc. ISIE*, Jun. 2011, pp. 340–346.

[32] K. Ma and F. Blaabjerg, "Multilevel converters for 10 MW wind turbines," in *Proc. EPE*, Birmingham, U.K., 2011, pp. 1–10.

[33] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. Portillo, M. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1002–1016, Jun. 2006.

[34] D. Krug, S. Bernet, S. S. Fazel, K. Jalili, and M. Malinowski, "Comparison of 2.3-kV medium-voltage multilevel converters for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2979–2992, Dec. 2007.

[35] J. Rodriguez, S. Bernet, P. K. Steimer, and I. E. Lizama, "A survey on neutral-point-clamped inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2219–2230, Jul. 2010.

[36] R. Teichmann and S. Bernet, "A comparison of three-level converters versus two-level converters for low-voltage drives, traction, and utility applications," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 855–865, May/Jun. 2005.

[37] T. Bruckner, S. Bernet, and H. Guldner, "The active NPC converter and its loss-balancing control," *IEEE Trans. Ind. Electron.*, vol. 52, no. 3, pp. 855–868, Jun. 2005.

[38] O. S. Senturk, L. Helle, S. Munk-Nielsen, P. Rodriguez, and R. Teodorescu, "Medium voltage three-level converters for the grid connection of a multi-MW wind turbine," in *Proc. EPE*, 2009, pp. 1–8.

[39] H. Hosoda and S. Peak, "Multi-level converters for large capacity motor drive," in *Proc. IPEC*, 2010, pp. 516–522.

[40] M. Altin, O. Goksu, R. Teodorescu, P. Rodriguez, B. Bak-Jensen, and L. Helle, "Overview of recent grid codes for wind power integration," in *Proc. OPTIM*, 2010, pp. 1152–1160.

[41] M. Malinowski, K. Gopakumar, J. Rodriguez, and M. A. Peérez, "A survey on cascaded multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2197–2206, Jul. 2010.

[42] B. Engel, M. Victor, G. Bachmann, and A. Falk, "15 kV/16.7 Hz energy supply system with medium frequency transformer and 6.5 kV IGBTs in resonant operation," in *Proc. EPE*, Toulouse, France, Sep. 2–4, 2003.

[43] S. Inoue and H. Akagi, "A bidirectional isolated DC-DC converter as a core circuit of the next-generation medium-voltage power conversion system," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 535–542, Mar. 2007.

[44] F. Iov, F. Blaabjerg, J. Clare, O. Wheeler, A. Rufer, and A. Hyde, "UNIFLEX-PM-A key-enabling technology for future European electricity networks," *EPE J.*, vol. 19, no. 4, pp. 6–16, 2009.

[45] D. Schreiber, "Power converter circuit arrangement for generators with dynamically variable power output," U.S. Patent 6 680 856, Jan. 20, 2004.

[46] B. Andresen and J. Birk, "A high power density converter system for the Gamesa G10x 4.5 MW Wind turbine," in *Proc. EPE*, Aalborg, Denmark, 2007, pp. 1–7.

[47] R. Jones and P. Waite, "Optimised power converter for multi-MW direct drive permanent magnet wind turbines," in *Proc. EPE*, 2011, pp. 1–10.

[48] J. Kang, N. Takada, E. Yamamoto, and E. Watanabe, "High power matrix converter for wind power generation applications," in *Proc. ICPE ECCE-Asia*, 2011, pp. 1331–1336.

[49] *The EU Climate and Energy Package*, Mar. 2007. European Commission Climate Action.

[50] B. Hahn, M. Durstewitz, and K. Rohrig, *Reliability of Wind Turbines—Experience of 15 Years With 1500 WTs*. Kassel, Germany: ISET, 2006.

[51] J. Lutz, H. Schlangenotto, U. Scheuermann, and R. W. De Doncker, *Semiconductor Power Devices Physics, Characteristics, Reliability*. Berlin, Germany: Springer-Verlag, 2011.

[52] E. Wolfgang, L. Amigues, N. Seliger, and G. Lugert, "Building-in reliability into power electronics systems," in *Proc. World Electron. Packag. Syst. Integr.*, 2005, pp. 246–252.

[53] D. Hirschmann, D. Tissen, S. Schroder, and R. W. De Doncker, "Inverter design for hybrid electrical vehicles considering mission profiles," in *Proc. IEEE Conf. Veh. Power Propulsion*, Sep. 7–9, 2005, pp. 1–6.

[54] S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran, and P. Tavner, "Condition monitoring for device reliability in power electronic converters: A review," *IEEE Trans. Power Electron.*, vol. 25, no. 11, pp. 2734–2752, Nov. 2010.

[55] J. Due, S. Munk-Nielsen, and R. Nielsen, "Lifetime investigation of high power IGBT modules," in *Proc. EPE*, Birmingham, U.K., pp. 1–8.

[56] K. Ma, F. Blaabjerg, and M. Liserre, "Thermal analysis of multilevel grid side converters for 10 MW wind turbines under low voltage ride through," in *Proc. ECCE*, 2011, pp. 2117–2124.

[57] K. Ma, M. Liserre, and F. Blaabjerg, "Reactive power influence on the thermal cycling of multi-MW wind power inverter," in *Proc. IEEE APEC*, Orlando, FL, 2012, to be published.

Frede Blaabjerg (S'86–M'88–SM'97–F'03) received the M.Sc.EE. and Ph.D. degrees from Aalborg University, Aalborg East, Denmark, in 1987 and 1995, respectively.

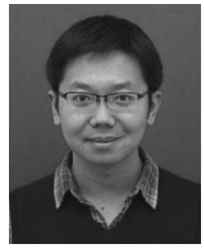
He was employed at ABB-Scandia, Randers, from 1987 to 1988. From 1988 to 1992, he was a Ph.D. student at Aalborg University, where he became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998. He has been a part-time Research Program Leader at the Research Center Risoe, Roskilde, Denmark, working with wind turbines. From 2006 to 2010, he was the Dean of the Faculty of Engineering, Science and Medicine at Aalborg University. He was a Visiting Professor at Zhejiang University, Hangzhou, China, in 2009. His research areas are power electronics and applications like wind turbines, PV systems, and adjustable-speed drives.

Dr. Blaabjerg received the 1995 Angelos Award for his contribution to modulation technique and the Annual Teacher Prize from Aalborg University, also 1995. In 1998, he received the Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society. He has received ten IEEE prize paper awards and another prize paper award at PELINCEC Poland 2005. He received the IEEE Power Electronics Society Distinguished Service Award in 2009 as well as the EPE-PEMC 2010 Council Award. Since 2006, he has been Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS. He was a Distinguished Lecturer for the IEEE Power Electronics Society from 2005 to 2007, and a Distinguished Lecturer for the IEEE Industry Applications Society from 2010 to 2011.

Marco Liserre (S'00–M'02–SM'07) received the M.Sc. and Ph.D. degrees in electrical engineering from Bari Polytechnic, Bari, Italy, in 1998 and 2002, respectively.

He is an Associate Professor at Bari Polytechnic, teaching courses on power electronics, industrial electronics, and electrical machines. He has published 153 technical papers, 38 of them in international peer-reviewed journals, three chapters of a book and a book, *Grid Converters for Photovoltaic and Wind Power Systems* (IEEE-Wiley, 2011). These works have received more than 3500 citations. He has been a Visiting Professor at Aalborg University, Aalborg East, Denmark, where he is currently cooperating within the Center Of Reliable Power Electronics with Alcala de Henares University, Spain, and Christian-Albrechts University of Kiel, Kiel, Germany, as Mercator Professor.

Dr. Liserre is member of the IEEE Industry Applications, IEEE Power Electronics, IEEE Power Engineering, and IEEE Industrial Electronics Societies. He is Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE TRANSACTIONS ON POWER ELECTRONICS, and IEEE TRANSACTIONS ON SUSTAINABLE ENERGY. He was Founder and Editor-in-Chief of the *IEEE Industrial Electronics Magazine*, Founder and the Chairman of the Technical Committee on Renewable Energy Systems, Co-Chairman of the International Symposium on Industrial Electronics (ISIE 2010), IES Vice-President responsible for publications. He has received the IES 2009 Early Career Award, the IES 2011 Anthony J. Hornfeck Service Award, and the 2011 Industrial Electronics Magazine best paper award. He is senior member of the IES AdCom.



Ke Ma (S'09–M'11) received the B.Sc. and M.Sc. degrees in electrical engineering from Zhejiang University, Hangzhou, China, in 2007 and 2010, respectively. He is currently working toward the Ph.D. degree in the Department of Energy Technology, Aalborg University, Aalborg East, Denmark.

His research interests are multilevel power electronics converters and their application in wind power generation systems.