Future on Power Electronics for Wind Turbine Systems

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***Abstract*— Wind power is still the most promising renewable energy in the year of 2013. The wind turbine system (WTS) started with a few tens of kilowatt power in the 1980s. Now, multimegawatt wind turbines are widely installed even up to 6–8 MW. There is a widespread use of wind turbines in the distribution networks and more and more wind power stations, acting as power plants, are connected directly to the transmission networks. As the grid penetration and power level of the wind turbines increase steadily, the wind power starts to have significant impacts to the power grid system. Therefore, more advanced generators, power electronic systems, and control solutions have to be introduced to improve the characteristics of the wind power plant and make it more suitable to be integrated into the power grid. Meanwhile, there are also some emerging technology challenges, which need to be further clarified and investigated. This paper gives an overview and discusses some development trends in the technologies used for wind power systems. First, the developments of technology and market are generally discussed. Next, several state-of-the-art wind turbine concepts, as well as the corresponding power electronic converters and control structures, are reviewed, respectively. Furthermore, grid requirements and the technology challenges for the future WTS are also addressed.**

***Index Terms*— Future power electronics, wind power.**

I. Introduction

AS THE fast growing capacity and more significant impacts to the power grid by wind turbine system (WTS), the power electronic technologies used in wind power application have changed dramatically during the last 30 years [1]–[18]. In the 1980s, the power electronics for wind turbines was just a soft starter used to initially interconnect the squirrel-cage induction generator with the power grid, and only simple thysistors were applied and they did not need to carry the power continuously [2]. In the 1990s the power electronic technology was mainly used for the rotor resistance control of wound-rotor induction generator, where more advanced diode bridges with a chopper were used to control the rotor resistance for generator [4], especially at nominal power operation to reduce mechanical stress and loading. Since 2000, even more advanced back-to-back (BTB) power converters were introduced in large scale which started to regulate the generated power from the wind turbines. First mostly in the partial-scale power capacity for the doubly fed induction generator (DFIG) [11]–[15], then in the full-scale power capacity for the asynchronous/synchronous generator (A/SG) [1], [6], [28]–[33]. By introducing the BTB power electronics converters (PECs), it is possible to fully control the extracted power from the wind turbines, and also provide ancillary services to the grid. Power electronics gradually become more and more advanced and bring in significant performance improvements for the wind turbines—not only reducing the mechanical stress and increase the energy yield, but also enable the whole WTS to act like a completely controllable generation unit being able to much better integrate the wind power into the power grid [2]–[6], [34]–[37].

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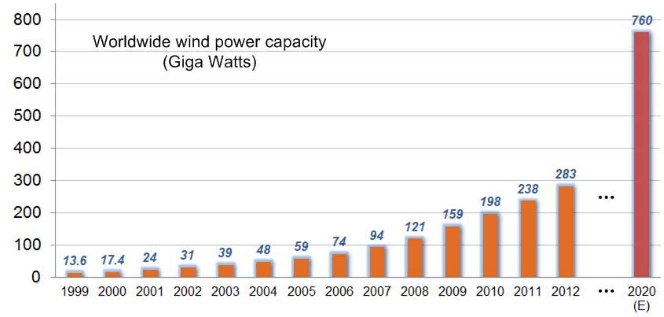

Fig. 1. Global cumulative installed wind power capacity from 1999 to 2020.

The scope of this paper is to give a status overview and discuss some technology trends of power electronics used for wind power application. Initially, the technology and market developments of wind power generation are generally introduced. Next two dominant wind turbine concepts as well as the potential converter topologies are addressed. Then some control methods and demands are briefly explained for the state-of-theart wind turbines. Furthermore, the emerging challenges for future wind power generation are discussed and some final conclusions are given.

II. Development of Wind Power Generation

The cumulative wind power capacity from 1999 to 2020 is shown in Fig. 1, and it can be seen that the wind power has grown fast to a capacity of 283 GW with ∼45 GW installed only in 2012, and this number is expected to achieve 760 GW in 2020 on moderate scenario [9]. The wind power grows more significant than any other renewable energy sources and is becoming really an important player in the modern energy supply system. As an extreme example Denmark has a high penetration by wind power and today >30% of the electric power consumption is covered by wind. This country has even the ambition to achieve 100% nonfossil-based power generation system by 2050 [10].

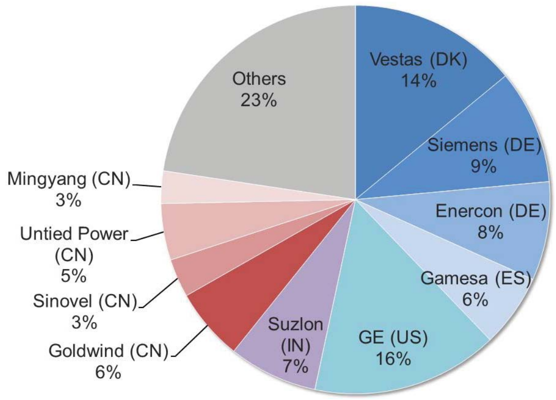

Fig. 2. Distribution of wind turbine market share by the manufacturers in 2012 [9].

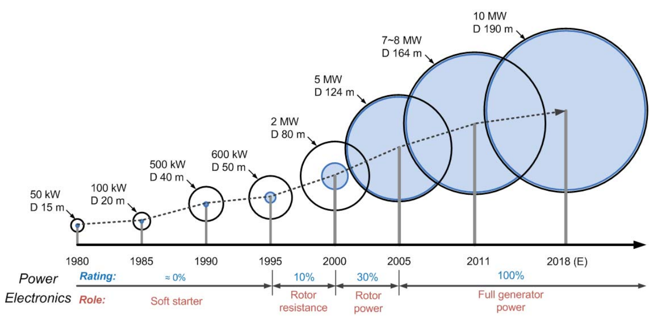

Fig. 3. Evolution of wind turbine size and the power electronics seen from 1980 to 2018 (estimated). Blue circle: the power coverage by power electronics.

Regarding the markets and manufacturers, the U.S. became the largest markets with over 13.1 GW capacity installed in 2012, together with China (13 GW) and the EU (11.9 GW) sharing around 87% of the global market. The Danish company Vestas first gives out the top position among the largest manufacturers since 2000, while GE catches up to the first because of the strong U.S. market in 2012. Fig. 2 summarizes the worldwide top suppliers of wind turbines in 2012. It is seen that there are four Chinese companies in the top 10 manufacturers with a total market share of 16.6%, which is a significant drop compared with the 26% in 2011 [9].

In addition to the quick growth in the total installed capacity, the size of individual wind turbine is also increasing dramatically to obtain a reduced price per generated kilowatt hour. In 2012, the average turbine size delivered to the market was 1.8 MW, among which the average offshore turbine has achieved a size of 4-MW. The growing trends of emerging turbine size between 1980 and 2018 are shown in Fig. 3, where the development of power electronics in the WTS (rating coverage and function role) is also shown. It is noted that the cutting-edge 8-MW wind turbines with a diameter of 164 m have already shown up in 2012 [7]. Right now most of the turbine manufacturers are developing products in the power range 4.5–8 MW, and it is expected that more and more large wind turbines with multimegawatt power level, (even up to 10-MW will appear in 2018), will be present in the next decade—driven mainly by the considerations to lower down the cost of energy [9].

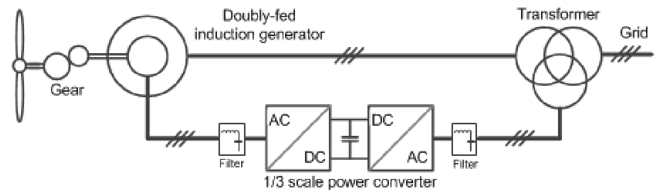

Fig. 4. Variable-speed wind turbine with partial-scale power converter and a DFIG.

III. State-of-the-Art Configurations and Power Electronics for Wind Turbines

The development of the wind turbine technology has been steady for the last 35 years [1]–[6]. Depending on the types of generator, power electronics, speed controllability, and the way in which the aerodynamic power is limited the wind turbine designs can generally be categorized into several concepts [3]–[5]. In these wind turbine concepts, the power electronics play quite different roles in the WTS and has various power rating coverages of the system, as shown in Fig. 3. Until now, the configuration of DFIG equipped with partial-scale power converter is dominating on the market, but in very near future the configuration with synchronous generator (SG) with full-scale power converter is expected to take over. Actually, the solutions with full-scale power converter are becoming the preferred technology choices in the best selling power ranges of the wind turbines [6], [7]. In the following, these two state-of-the-art wind turbine concepts are going to be introduced.

A. DFIG With Partial-Scale Power Converter

This wind turbine concept is the most adopted solution nowadays and it has been used extensively since 2000s. As shown in Fig. 4, a PEC is adopted in conjunction with the DFIG. The stator windings of DFIG are directly connected to the power grid, whereas the rotor windings are connected to the power grid by the converter with normally 30% capacity of the wind turbine [11], [12]. In this concept, the frequency and the current in the rotor can be flexibly regulated and thus the variable speed range can be extended to a satisfactory level. The smaller converter capacity makes this concept attractive seen from a cost point of view. Its main drawbacks are however, the use of slip rings and the challenging power controllability in the case of grid faults—these disadvantages may comprise the reliability and may be difficult to completely satisfy the future grid requirements as claimed in [13] and [14].

The two-level pulsewidth modulation voltage source converter (2L-PWM-VSC) is the widely used converter topology so far for the DIFG-based wind turbine concept as the power rating requirement for the converter is limited. Normally two 2L-PWM-VSCs are configured in a BTB structure in the WTS, as shown in Fig. 5, which is called two-level BTB (2L-BTB) for convenience. A technical advantage of the 2L-BTB solution is the full power controllability (four quadrant operation) with a relatively simple structure and few components, which contribute to well-proven robust/reliable performances as well as advantage of cost [15].

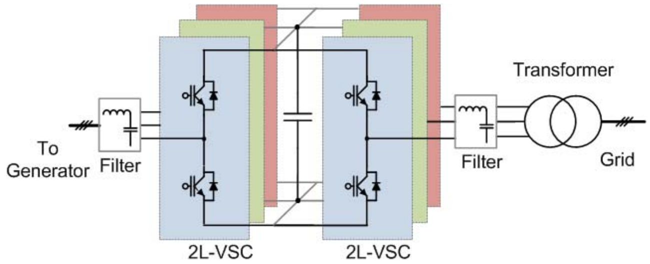

Fig. 5. 2L-BTB voltage source converter for wind turbine.

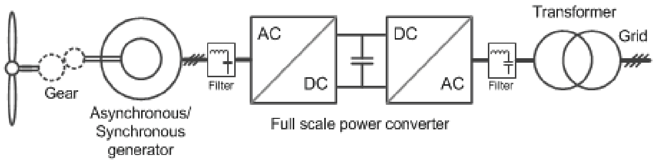

Fig. 6. Variable-speed wind turbine with full-scale power converter.

B. A/SG With Full-Scale Power Converter

The second important concept that is popular for the newly developed and installed wind turbines is shown in Fig. 6. It introduces a full-scale power converter to interconnect the power grid and stator windings of the generator, thus all the generated power from the wind turbine can be regulated. The asynchronous generator, wound rotor SG (WRSG) or permanent magnet SG (PMSG) have been reported as solutions to be used. The elimination of slip rings, simpler or even eliminated gearbox, full power and speed controllability as well as better grid support ability are the main advantages compared with the DFIG-based concept. The more stressed and expensive power electronic components as well as the higher power losses in the converter are, however, the main drawbacks for this concept.

As the converter in this concept needs to carry all the generated power by wind turbines, e.g., up to 10-MW, the 2L-BTB converter topology at this power level may suffer from large switching loss and many devices may need to be connected in parallel also the cabling in case of low voltage level can be a great design/physical challenge. Therefore, it becomes very difficult for a single 2L-BTB topology to achieve acceptable performance for the full-scale wind power converter, even though having the cost advantage.

To handle the growing power with the exiting 2L-BTB technology, some multicell converter configurations are introduced (i.e., parallel/series connection of 2L-BTB converter cells). Fig. 7(a) shows a multicell solution adopted by Gamesa in the 4.5-MW wind turbines [16], which have several 2L-BTB converters paralleled both on the generator and grid sides. Siemens also introduce the similar solution in their best selling multimegawatt wind turbines, as shown in Fig. 7(b) [17]. The standard and proven low voltage converter technologies as well as redundant and modular characteristics are the main advantages. This converter configuration is the state-of-the-art solution in the industry for the wind turbines with power level >3 MW.

With the abilities of achieving higher voltage and power level, multilevel converters may become more preferred candidates in the full-scale converterbased concept [18]–[20]. The three-level neutral point diode clamped (3L-NPC) topology is one of the most commercialized multilevel topologies on the market. Similar to the 2L-BTB, it is usually configured as a BTB structure in the wind power application, as shown in Fig. 8, which is called 3L-NPC BTB for convenience. The 3L-BTB solution achieves one more output voltage level and less dv/dt stress compared with the counterpart of 2L-BTB, thus it is possible to convert the power at medium voltage with lower current, less paralleled devices, and smaller filter size. The midpoint voltage fluctuation of the dc bus can be a drawback of the 3L-NPC BTB. This problem has been extensively researched and it is considered to be improved by the controlling of redundant switching states [21]–[23]. It is, however, found that the loss distribution is unequal between the outer and inner switching devices in a switching arm [24]–[26], and this problem might lead to a derated power capacity when it is practically used.

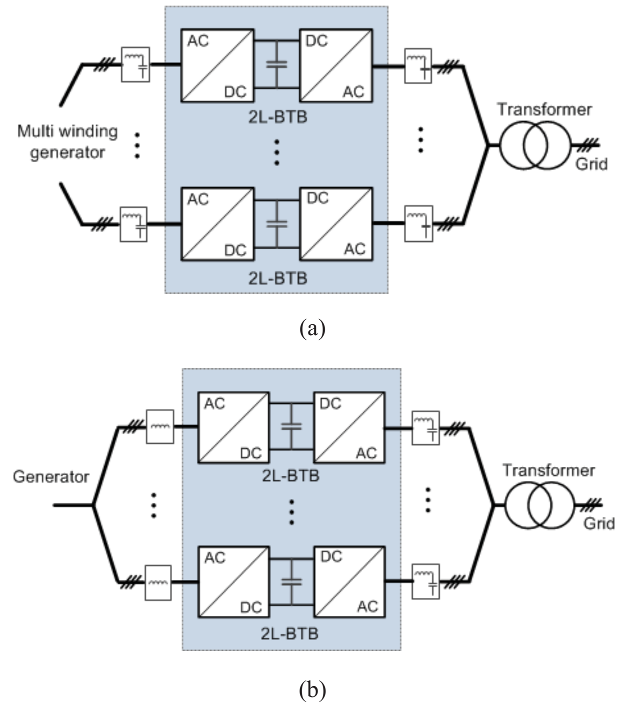

Fig. 7. Multicell converter with paralleled 2L-BTB converter cells. (a) With multi-winding generator. (b) With regular winding generator.

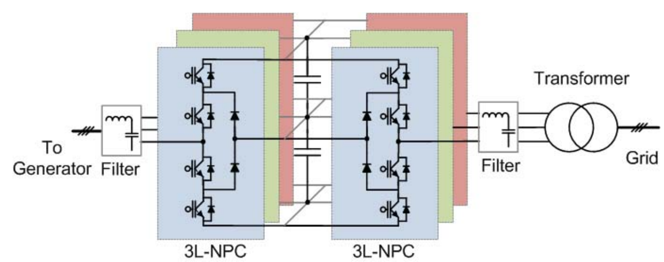

Fig. 8. 3L-NPC BTB converter for wind turbine.

IV. Control Structure of WTS

Controlling a wind turbine involves both fast and slow control dynamics [27]–[33], as shown in Fig. 9, where a general

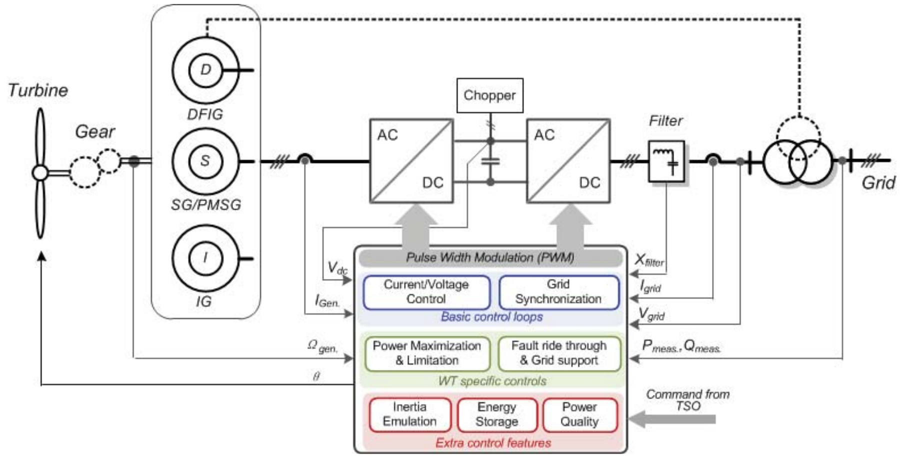

Fig. 9. General control structure for modern wind turbines.

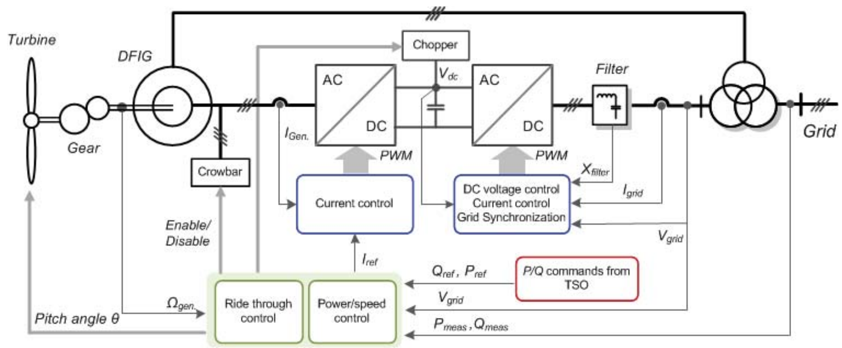

Fig. 10. Control of a wind turbine with DFIG.

control structure for a WTS, including turbine, generator, filter, and converter, is shown. The wind turbine concept can either be the type shown in Fig. 4, or the type shown in Fig. 6. Generally, the power flowing in and out of the generation system has to be managed carefully. The generated power by the turbines should be controlled by means of mechanical parts (e.g., pitch angle of blades, yawing system, etc.). Meanwhile, the whole control system has to follow the power production commands given by distribution system operator (DSO)/transmission system operator (TSO).

More advanced features of the wind turbine control may be considered such as the maximization of the generated power, ride through operation of the grid faults, and providing grid supporting functions in both normal and abnormal operations, and so on. In the variable-speed wind turbine concept, the current in the generator will typically be changed by controlling the generator side converter, and thereby the rotational speed of turbine can be adjusted to achieve maximum power production based on the available wind power. In respect to operation under grid fault, coordinated control of several subsystems in the wind turbine such as the generator/grid side converters, braking chopper/crowbar, and pitch angle controller are necessary.

Finally, the basic controls such as current regulation, dc bus stabilization, and the grid synchronization have to be quickly performed by the wind power converter, where the proportional-integral controller and proportional-resonant controllers are typically used [31], [34], [35].

As an example, the control methods for a DFIG-based WTS are shown in Fig. 10. Below maximum power production, the wind turbine will typically vary the rotational speed proportional with the wind speed and keep the pitch angle θ fixed. At very low wind speed, the rotational speed will be fixed at the maximum allowable slip to prevent over voltage of generator output. A pitch angle controller is used to limit the power when the turbine output is above the nominal power. The total electrical power of the WTS is regulated by controlling the DFIG through the rotor side converter. The control strategy of the grid side converter is simply just to keep the dc-link voltage fixed. It is noted that a trend is to use a crowbar connected to the rotor of DFIG to improve the control performance under grid faults [13], [14].

Another example for the control structure used for full-scale converter-based wind turbine concept is shown in Fig. 11. An advantage of this turbine system is that the dc link performs some kinds of control decoupling between the turbine and the grid. The dc link will also give an option for the wind turbines to be connected with energy storage units, which can better manage the active power flow into the grid system—this feature will further improve the grid supporting abilities of the wind turbines. The generated active power of the WTS is controlled by the generator side converter, whereas the reactive power is controlled by the grid side converter. It is noted that

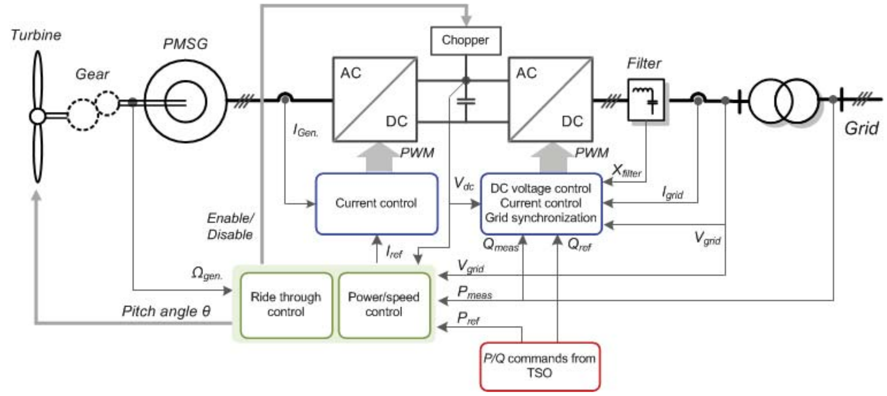

Fig. 11. Control of active and reactive power in a wind turbine with multipole PMSG.

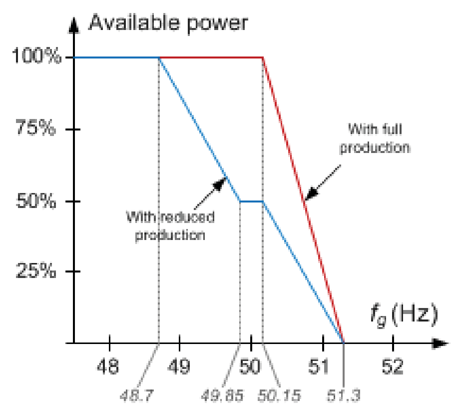

Fig. 12. Frequency control profiles for the wind turbines connected to the Danish grid [39].

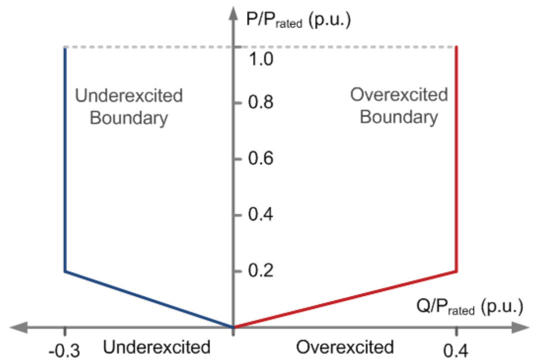

Fig. 13. Reactive power ranges under different generating powers for a wind farm specifiedby the Danish and German grid codes [40].

a dc chopper is normally introduced to prevent overvoltage of dc link in case of grid faults, when the extra turbine power needs to be dissipated as the sudden drop of grid voltage.

V. Grid Integration of Wind Turbine System

The fluctuation and unpredictable features of wind energy are nonpreferred for grid operation. Most of the countries have strict requirements for the behavior of wind turbines, known as grid codes, which are updated regularly [36]–[40]. Basically, the grid codes are always trying to make the WTS to act as a conventional power plant from the electrical utility point of view. That means the WTS should not only be a passive power source simply injecting available power from the wind, but also behave like an active generation unit, which can wisely manage the delivered active/reactive power according to the demands, and provide frequency/voltage support for the power grid. Examples of the state-of-the-art grid supporting requirements are given in the following. They are specified either for individual wind turbine or for the whole wind farm.

According to most of the grid codes, the individual wind turbines must be able to control the active power at the point of common coupling. Normally, the active power has to be regulated based on the grid frequency, e.g., in Denmark, Ireland and Germany, so that the grid frequency can be somehow maintained. As an example, the characteristic of frequency supports in the Danish grid codes is shown in Fig. 12, where the active power should be decreased when the frequency rises >48.7 or 50.15 Hz depending on the power reserving strategy [39]. Similarly, the reactive power delivered by the WTS also has to be regulated in a certain range. As shown in Fig. 13, both the Danish and German grid codes give a range of the reactive power delivered by the WTS to the active power output [40]—this will lead to larger MVA capacity when designing the whole converter system. In addition, the TSO will normally specify the reactive power range of the WTS according to the grid voltage levels. It is noted that this reactive power control should be realized slowly under the time constant of minutes in steady-state operation [36].

In addition to the normal operation, the TSOs in different countries have issued strict grid supporting requirements for the WTS under grid faults. As shown in Fig. 14 [36], [37], in which the boundaries with various grid voltage dip amplitudes as well as the allowable disturbing time are defined for a wind farm. It is becoming a need that the WTS should also provide reactive power (up to 100% current capacity) to contribute to the voltage recovery when the grid voltage sag is present. Fig. 15 shows the required amount of reactive current against to the grid voltage amplitude by the German [40] and Danish grid codes [39]. This demand is relatively difficult to be met by the wind turbine concept in Fig. 4, and other power quality units like STATCOMs may probably be introduced to help the WTS in achieving this tough requirement.

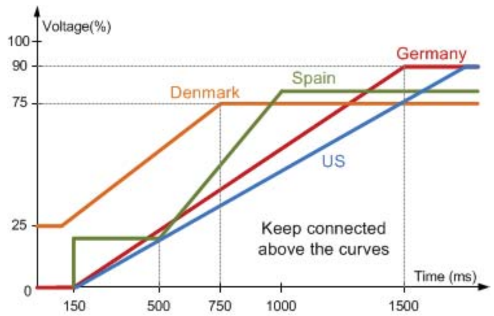

Fig. 14. Voltage profile for low-voltage ride-through capability of the wind turbines by different countries [37].

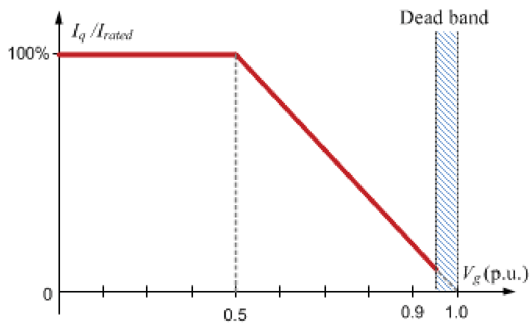

Fig. 15. Reactive current requirements for a wind farm during grid sags by the German and Danish grid codes [39], [40].

The requirements for more grid supports by wind turbines on one hand have increased the cost per produced kilowatt hour, but on the other hand, made the wind energy more suitable to be largely used and integrated into the power grid. It can be predicted that the stricter grid codes in the future will keep challenging the WTS and pushing forward the power electronic technologies. Table I compares the features of conventional power plant, wind turbine generation (WTG) system in the past and WTG system nowadays, where the major grid integration performances are focused. It can be concluded that by introducing more advanced power electronics, controls, and grid regulations, the start-of-the-art WTS equipped with SG and full-scale power converter can more or less emulate the behaviors of conventional power plants, making the wind power technology to be more suitable integrated into the power grid.

VI. Technology Challenges for Power Electronics in WTS

In this section, several emerging technology challenges for the power electronics in the future WTS are addressed. The discussions will mainly focus on technology issues of power electronics in respect to cost, reliability, grid integration, new power electronics circuits and devices.

A. Lower Levelized Cost of Energy

The cost issues are the most important considerations for the technology, which will determine the feasibility of certain energy technologies to be widely used in the future. The competitive cost advantage is the main reason why the wind power showed the most significant growth in the last few decades compared with the other renewable energy sources. To quantify and compare the cost for different energy technologies, levelized cost of energy (LCOE) index is generally used [41]. LCOE represents the price at which the electricity is generated from a specific energy source over the whole lifetime of the generation unit. It is an economic assessment of the cost of the energy generating system including all the costs such as initial investment, development cost, capital cost, operations and maintenance cost, cost of fuel, and so on. LCOE can be defined in a single formula as follows:

$$\text{LCOE} = \frac{C_{\text{Dev}} + C_{\text{Cap}} + C_{\text{O\& M}}}{E_{\text{Annual}}}. \quad (1)$$

It is noted that the initial development cost C_{Dev}, capital cost C_{Cap}, and the cost for operation and maintenance $C_{O\&M}$ are first levelized to annual average cost seen over the lifetime of the generation system, and then divided by the average annual energy production in the whole lifetime E_{Annual}. From (1) it is clear that to reduce the cost of energy, one effective way is to reduce the cost for development, capital, operation, and maintenance, the other effective way is to extend the energy production or increase the lifetime of the generation system. As an example the LCOE for offshore wind power of Denmark and UK is between 140 and 180 EUR/MWh in 2010 according to the studies carried in [42], and this number is expected to reduce 50% by 2020 in the span of 67–90 EUR/MWh, providing the lifetime of wind turbine increases from 20 to 25 years and other significant cost reductions are achieved.

Fig. 16 shows another example of the U.S. estimated LCOE for several promising renewable energy technologies in 2018 [43]. It can be seen that the cost distribution of different technologies varies a lot. where the onshore wind power still shows cost advantages compared with other renewable energy sources. It can be also expected that in the U.S., the capital cost may still be dominant for most of the renewable energy technologies for the next decade.

As more power electronics are introduced in the energy system to improve the performances of power generation, the cost for the power electronics is becoming more important and it depends a lot on the specific wind turbine concepts. In the WTS, there are some special cost considerations which impose challenges for the design and the selection of power electronics.

For instance, the needs for higher power capacity and full-scale power conversion will increase the cost for power semiconductors, passive components and corresponding cooling management—thereby more efficient circuits and devices are required. Additionally, because of the limited space in the nacelle or tower, a higher power density will be emphasized for the power converters and this may lead to extra cost for insulation materials and also compact design as the voltage level increases. In addition, the weight of the whole converter system should be limited as much as possible because it has to be placed in the nacelle or tower of the turbines. The long cable connections between the nacelle and tower–base range from dozens to hundreds of meters and may require higher voltage level in the power conversion stage to reduce the

TABLE I
COMPARISON OF GRID INTEGRATION PERFORMANCES BETWEEN CONVENTIONAL POWER PLANT AND WIND TURBINE PLANT, THE MORE + THE BETTER, 0 MEANS MODERATE, – MEANS NO SUCH ABILITY

Grid integration Features	Conventional power plant	WTG in the past (without/few PEC)	WTG nowadays/future (With PEC)
Active power control	+	0	+
Reactive power control	+	0 / -	++
Short circuit capability	++	+	++
Voltage backup	++	-	+
Power output Inertia	++	-	+
Frequency control	++	-	++
Black start capability	+	-	+

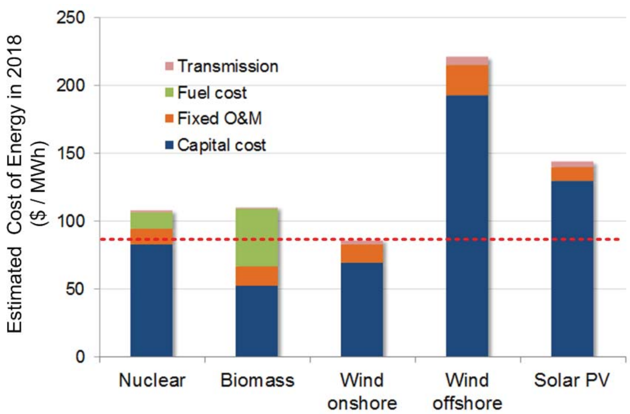

Fig. 16. Estimated LCOE for several renewable energy technologies in 2018. Source: Energy Information Administration and Annual Energy Outlook 2013 [43].

cable losses and cable weight. Furthermore remote locations of the wind turbines may increase the cost for installation and maintenance, which also demands high reliability, modularity and redundant design of the PEC.

B. Higher Reliability

The dramatic growth of total installation and also the individual capacity make the failures of wind turbines costly or even unacceptable from the point view of the TSO/grid owner. The failures of WTS will not only cause stability problems of the power grid because of sudden absence of a large amount of power capacity, but also results in high cost for repairing and maintenance especially for those large and remote-located wind turbines, additionally it will cause loss of production of the owner—leading to reduced total/annual energy production and thus increase the LCOE. As a result, the reliability performance is a critical design consideration for the next generation wind power converters. When looking at the failure rates and downtime distribution in individual wind turbine [45], it is found that the control and power electronic parts tend to have higher failure rate than the other subsystems with a factor of 2–4. That means the reliability improvements of power electronics will effectively reduce the cost of wind energy or LCOE.

The reliability research in power electronics has been carried out for decades and now is moving from a solely statistical approach that has been proven to be unsatisfactory in the automotive industry, to a more physical-based approach which involves not only the statistics but also the investigation and modeling of the root cause behind the failures [46]–[48]. As shown in Fig. 17, a diagram of possible activities for reliability analysis and improvement is illustrated. To achieve more cost-efficient and reliable power electronic systems, multidisciplinary approaches are necessary to be included that involve better mission profile mapping, stress analysis, strength modeling, statistical considerations, and also online monitoring/control of the converter for predictive maintenance. It is noted that a series of reliability design tools may be necessary to transfer, organize, and combine the relevant approaches to more insight reliability performances.

The stress analysis may focus on complete mission profile definition, converter design, stress estimation, and measurement. This group of disciplines will target a better establishment of the converter's loading profile, which can initiate the failure mechanisms of the critical components, such as thermal cycling in power devices [49], voltage increase in the dc bus [50], vibration, humidity, and other stress factors [51], [52].

The strength modeling may involve the identification, modeling, and accelerating test of failure mechanisms in the converter system, e.g., bond-wire lift-off and soldering crack inside the power modules [53]. The goal of this group of disciplines is to seek correlations between the established/measured

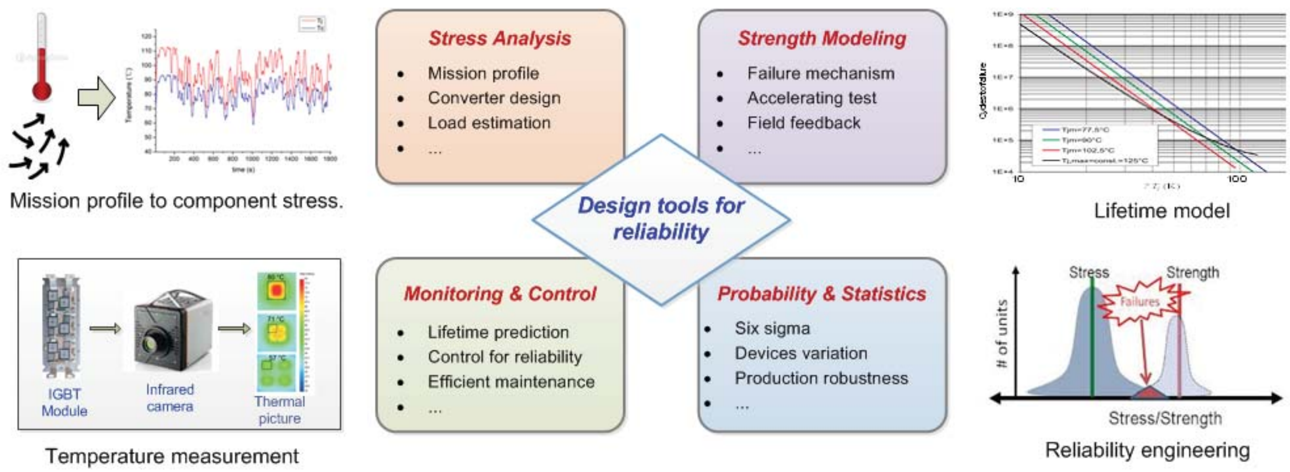

Fig. 17. Multidisciplinary approaches for more reliable power electronics.

stresses and the quantified fatigues/failures of the critical components.

The monitoring and control approach may relate to the lifetime monitoring [54], [55], junction temperature control methods [56], [57], and intelligent maintenance using prognostic methods. This group of disciplines will target to monitor and control the converter lifetime during operation. For example, the collector–emitter voltage V_{CE} of an insulated gate bipolar transistor (IGBT), which is subject to an accelerated test, experiences a sudden increase just before the IGBT failure [54] and therefore can be used for predictive maintenance in the WTS.

The probability and statistics may add the statistical distribution and correlation to the acquired stress, strength, and component configuration. This group of disciplines will target to enhance and validate the robustness of the designed converter and consider the severe usage of wind turbine, six sigma strategies in the design and quality variations of components to give estimation about failure rate in the next 10–25 years of the product.

With the better models and understanding of the reliability of power electronics, the LCOE of wind power may be significantly reduced because the design margins can be more accurately reserved, the loading of devices can be more intelligently modified, also the maintenance can be more wisely scheduled, achieving reduced cost for design and maintenance, and extended lifetime for the wind turbines.

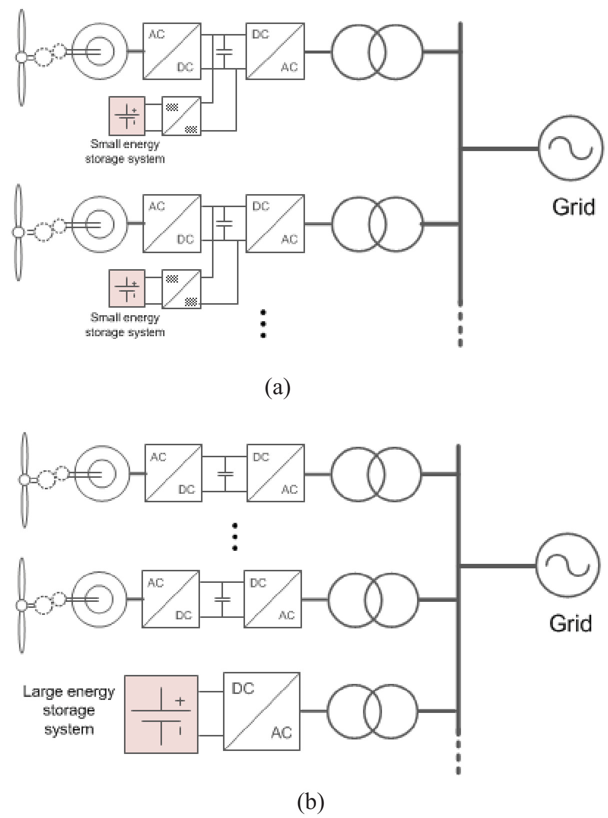

Fig. 18. Potential energy storage configurations for wind power plants to enable virtual power plant operation. (a) Distributed energy storage. (b) Centralized energy storage.

C. More Advanced Grid Integration Features

The grid codes nowadays reflect the trends of more penetration of wind energy into the power grid, and they just impose some basic requirements for the wind turbines to act more like the conventional power plants. It can be expected that to enable even larger-scale utilization of wind power in the future, more advanced grid interconnection requirements/features may be necessary not only for the wind turbine units, but also for the wind farms or even the whole distribution networks including the wind turbines.

1) Protection and Islanding Operation: To reduce the impact of the wind gust and ensure the security and stability of grid operation, the wind turbines or wind farms are preferred to be configured as distributed generation networks (with many small-size power stations connected to the medium voltage distribution grid), whose power flows and electrical behaviors are different compared with the traditional centralized generation networks (with only a few large-sized power stations connected to the high voltage transmission grid). Therefore the protection schemes of the future grid utilities with more wind power penetration should be also changed—resulting in a more

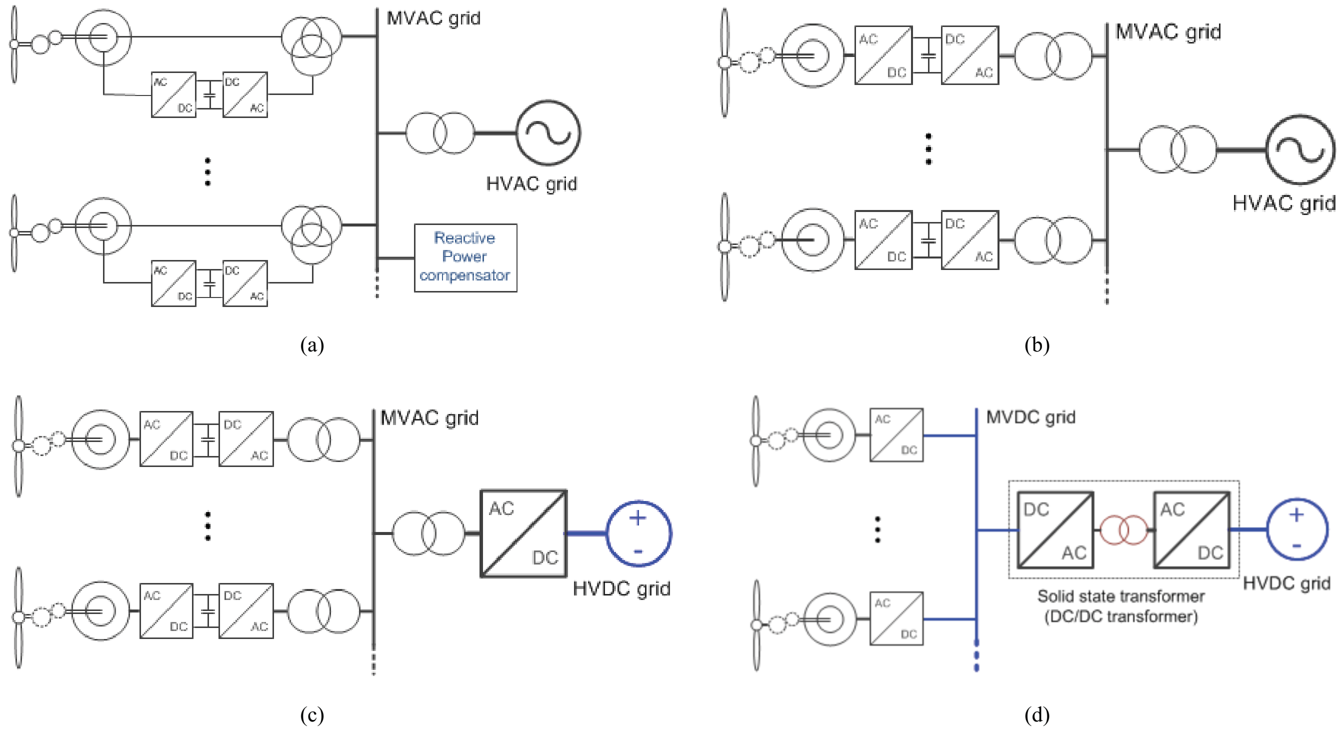

Fig. 19. (a) Potential wind farm configurations with ac and dc power deliveries. (a) DFIG system with an ac grid. (b) Full-scale converter system with ac grid. (c) Full-scale converter system with transmission dc grid. (d) Full-scale converter system with both distribution and transmission dc grids.

distributed protection structure and may allow the islanding operation of some wind turbine units and local loads, which are composed as microgrids. Such features demand more control efforts for the future WTS in respect to the grid fault identification, active and reactive power coordination, energy storage, signal communication, and voltage stabilization.

Moreover, as the growing proportion of wind power in the power grid, more advanced grid requirements that usually are targeted to large power plants can also be addressed to the wind turbine itself, e.g., in the case of the faults and shutting down of transmission networks, the WTSs may need the abilities to do black start if the faults are cleared, (i.e., restart the power generation without any power supply from the grid).

To achieve these more advanced features of grid interconnection, some energy storage systems may be needed for the future wind turbines and the wind farms. The storage system can be configured locally for each wind turbine unit, as shown in Fig. 18(a), or be configured centrally for several wind turbines/wind farms as shown in Fig. 18(b), It is noted that the energy storage could be in the form of battery, Super-capacitor, flywheel, hydropower station, or even combined energy storage systems, depending on the cost as well as the needed energy amount and control dynamics. Such WTS with energy storage will also be ready to operate as a primary controller in the case of enough energy is prestored and the wind power plant is approved to support this power system control feature.

2) *Configurations of Wind Power Plants:* As the wind power capacity grows, large wind farms that consist of many wind turbines are being developed. These wind farms may have significant impacts to the grids, and therefore they will play an important role on the power quality and the control of the power grid systems. The power electronic technology is again an important part for both the system configurations and the control of the wind farms to fulfil the growing grid demands. Some existing and future potential configurations of the wind farms are shown in Fig. 19.

A wind farm equipped with DFIG-based WTSs is shown in Fig. 19(a). Such a wind farm system is in operation in Denmark as a 160-MW offshore wind power station. Because of the limitation of the reactive power capability, a centralized reactive power compensator like STATCOM may be needed to fully satisfy future grid requirements.

Fig. 19(b) shows another wind farm configuration equipped with a WTS based on full-scale power converter. Because the reactive power controllability is significantly extended, the grid side converter in each of the generation unit can be used to provide the required reactive power individually, leading to reactive power compensator-less solutions.

For long-distance power transmission from an offshore wind farm, high voltage direct current (HVDC) may be an interesting option because the efficiency is improved and no voltage compensators are needed [58], [59]. A typical HVDC transmission solution for wind power is shown in Fig. 19(c), in which the medium ac voltage of the wind farm output is converted into a high dc voltage by a boost transformer and high-voltage rectifier.

Another possible wind farm configuration with HVDC transmission is shown in Fig. 19(d) where a Solid-state transformer (or dc/dc transformer) [60] is used to convert the low/medium dc voltage from each wind turbine output, to the

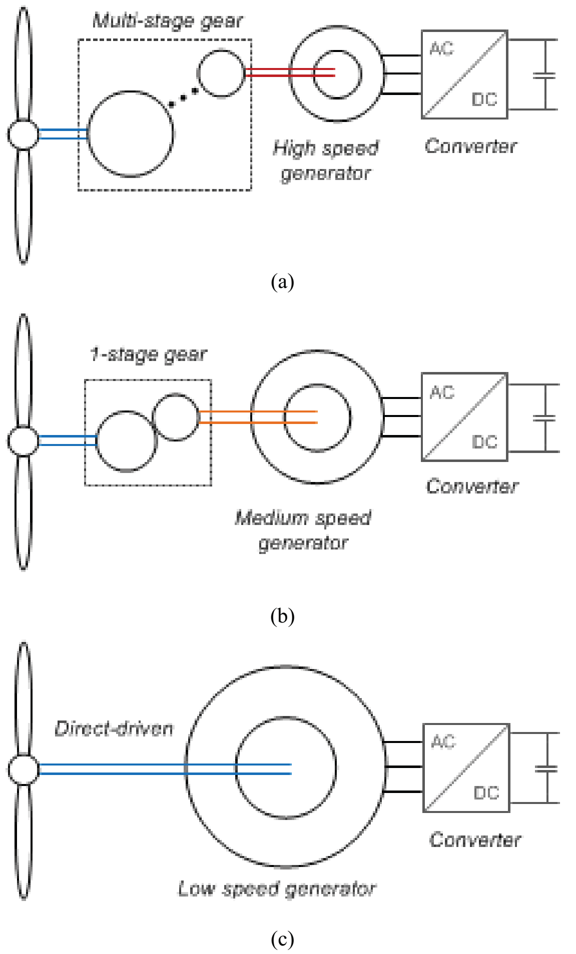

Fig. 20. Possible drive train and generation solutions for wind power system. (a) Multi-stage gear drive with high-speed generator. (b) One-stage gear drive medium-speed generator. (c) Direct drive with low-speed generator.

medium/high dc voltage for transmission, thus a full dc power delivery both in the distribution and transmission grids can be realized. It is claimed in [61] that the overall efficiency of the power delivery can be significantly improved compared with the configuration shown in Fig. 19(c)—mainly because of less converters and transformers in this dc transmission system. It can be a future solution for large wind farms to increase the overall efficiency of wind power plant.

D. Future Technologies for Wind Power Conversion

Nowadays, most of the erected wind turbines are based on the power conversion at low voltage level (< 690 V) and using induction, permanent magnet, or wound rotor synchronous generators. To satisfy the fast growing capacity and the tough challenges for the wind power system, advanced technologies that can realize more efficient and reliable wind power conversion are expected to appear in the near future, where the major changes could happen in the drive trains, generators, power converters, and semiconductor devices, by achieving power conversion at higher voltage level (1–10 kV).

1) Generator and Drive Train: Because of the experience for high robustness and relative cheap price in the motor drive applications, the high-speed induction/asynchronous generators are widely adopted in the WTS in the past and even

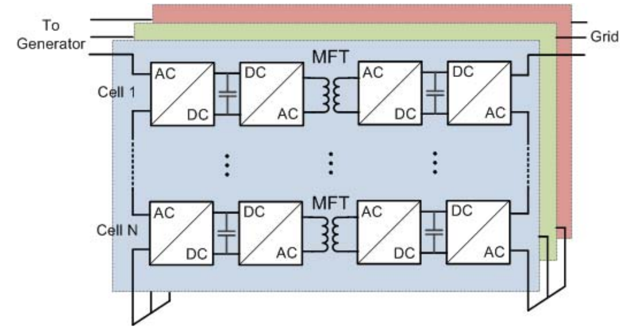

Fig. 21. Cascaded H-bridge converter with Medium Frequency Transformer for wind turbine.

nowadays. However, to adapt the different rotational speeds between the wind turbine and generator, a multi-stage gear box, which is normally heavy and bulky has to be used, as shown in Fig. 20(a). The multi-stage gear box has been a trouble maker in the wind power industry because of the unsatisfactory downtime as well as the high cost for maintenance [45]. Thereby, multipole low-speed SGs were introduced in the wind power application because the rotational speed can be designed to adapt to the wind turbine speed even with no gear/direct-driven solution, as shown in Fig. 20(c). As the power level of the individual wind turbines, however, keeps growing up even to 10 MW, it is becoming more and more difficult to get acceptable size and weight of the multipole generator at low rotational speed as the diameter is becoming huge. Actually in some of the newly presented wind turbines, which range from 5 to 8-MW, a tradeoff solution with one-stage gear driven is seen to be applied, as shown in Fig. 20(b), where the drive train is simpler and smaller than the solution in Fig. 20(a), meanwhile, a medium-speed SG can achieve smaller size than the generator solution in Fig. 20(c).

Nevertheless, the uncertain price for permanent magnet materials, which are popularly used in the existing multi-pole SGs, may limit the concepts in Fig. 20(b) and (c) to be further commercialized—calling for SG solutions with less/no permanent magnets in the future. That trend also gives possibilities for new PM-less generator technologies such as high temperature superconductor (HTS) generator, which compared with conventional generators is significantly smaller and lighter with larger air gap to eliminate the issues of tolerance or deformation—making it very suitable to be used in the wind power application if regardless cost [62]. In respect to some other PM-less technologies such as the low speed DFIG and switched reluctance generator, they do not seem to be suitable for multi-megawatt wind power conversion because of the requirements for small air gap, which makes the turbine installation difficult.

2) Power Electronics and Transformer: Because of the space limitation in the nacelle or in the tower of the wind turbines, a full-scale converter solution that avoids the bulky low-frequency transformer may become a promising solution for the future WTS. As shown in Fig. 21, this configuration shares the similar idea with the next generation traction converters [63], [64], and it is also proposed in the European UNIFLEX-PM project [65]. It is based on a structure of BTB cascaded H-bridge converter, with galvanic insulated dc/dc converters

TABLE II
SILICON POWER SEMICONDUCTOR DEVICES FOR WIND POWER APPLICATION

	IGBT module	IGBT Press-pack	IGCT Press-pack	SiC MOSFET module
Power Density	Low	High	High	Low
Reliability	Moderate	High	High	Unknown
Cost	Moderate	High	High	High
Failure mode	Open circuit	Short circuit	Short circuit	Open circuit
Easy maintenance	+	-	-	+
Insulation of heat sink	+	-	-	+
Snubber requirement	-	-	+	-
Thermal resistance	Large	Small	Small	Moderate
Switching loss	Low	Moderate	Moderate	Low
Conduction loss	Moderate	Moderate	Moderate	Large
Gate driver	Moderate	Moderate	Large	Small
Major manufacturers	Infineon, Semikron, Mitsubishi, ABB, Fuji	Westcode, ABB	ABB	Cree, Rohm, Mitsubishi
Medium voltage ratings	3.3 kV / 4.5 kV /6.5 kV	2.5 kV / 4.5 kV	4.5 kV /6.5 kV/10 kV	1.2 kV / 10 kV
Max. current ratings	1.5 kV / 1.2 kA / 750 A	2.3 kA / 2.4 kA	3.6 kA / 3.8 kA/ 2 kA	180 A / 120 A

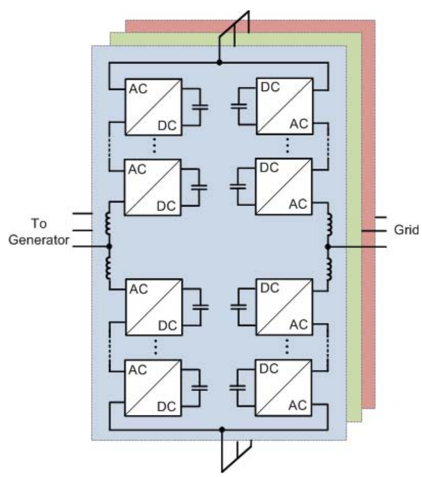

Fig. 22. Modular multilevel converters for wind turbine.

as an interface. The dc/dc converters have medium frequency transformer (MFT) operating at several kilohertz to dozens of kilohertz, thereby the transformer size can be significantly reduced. Moreover, because of the cascaded structure, it can be directly connected to the distribution power grid (10–33 kV) with high output quality, filter-less design, and also redundant ability—which are of high interest in wind power system. This solution would become more attractive if it can be placed in the nacelle of wind turbines because the heavy/bulky low frequency transformer can be replaced by the more compact and flexible configured power semiconductor devices.

Another future configuration for wind turbines that shares the similar idea with some of the emerging converters used for HVDC transmission [66], [67] is shown in Fig. 22. It is also based on a BTB structure with cascaded converter cells of 2L-VSC. One advantage of this configuration is the easily scalable voltage/power capability; therefore it can achieve very high power conversion at dozens of kilovolts with good modularity and redundancy. The output filter can also be eliminated because of significantly increased voltage levels. The useable voltage rating in the WTS, however may be greatly limited by the insulation materials of the generator. Moreover the low fundamental frequency of the generator outputs (which is the normal case for megawatt SG) may introduce large dc voltage fluctuation in the converter cells of the generator side, and thereby results in bulky capacitors in the converter system, which may be unpreferable for the wind power application.

3) Power Semiconductor Device: The power semiconductors are the backbone in the wind power converter and will determine many critical performances of the WTS such as the cost, efficiency, reliability, and modularity. The potential high-power silicon-based semiconductor technologies in the wind power application are among the module packaged IGBT, press-pack packaged IGBT, and the press-pack packaging integrated gate commutated thyristor (IGCT) [68]–[70]. Recently, there is a booming development of silicon carbide (SiC)-based devices, which are majorly in the form of metal–oxide–semiconductor field-effect transistor as well as diodes, although mainly targeted for low-voltage and low-power converter applications, they could be also the potential power devices used in wind power system.

The four types of power semiconductor devices have quite different characteristics and they are compared in Table II.

The module packaging technology of IGBT has a longer track record of applications and fewer mounting restrictions. However, because of the soldering and bond-wire connection of internal chips, module packaging devices may suffer from larger thermal resistance, lower power density, and higher failure rates [71]. The main trends to improve the packaging technology of IGBT module are to introduce pressure contact for eliminating the base plate and thus base plate soldering, sintering technology to avoid the chip soldering, as well as replaced bond-wire material to reduce the coefficient of thermal expansion—all lead to increased lifetime of module packaging IGBTs, as reported in [72].

The press-pack packaging technology improves the connection of chips by direct press-pack contacting, which leads to improved reliability (yet to be scientifically proved but known from industrial experience), higher power density (easier stacking for series connection), and better cooling capability. Press-pack IGCTs were first introduced into the medium-voltage motor drivers in the 1990s and has already become state-of-the-art technology in the applications of oil, gas, HVDC, power quality, and so on. However, IGCT has not yet been mass adopted in the WTS. As the power capacity of wind turbines grows up even to 10-MW, it can be expected that the press-pack packaging devices may become more promising for the future WTS.

In addition to the silicon power devices, the SiC-based device that is claimed to have better switching characteristics and lower power losses, are also promising in the future wind power systems. Although the existing power capacity of the SiC devices is still not enough for the wind power application, these new device technologies show great potential for some future wind converter structures, which consist of paralleled/cascaded converter cells, in which the requirements for voltage and current ratings are much lower. The main challenges for SiC-based devices are, however, the bonding technology, limitation of stray inductance either in the external circuit or inside the module, higher dv/dt stress, higher operational temperature, as well as thinner chips—all of these have to be carefully considered in the packaging and design of SiC-based converter system.

VII. Conclusion

The total installed and individual capacity of wind turbines have both been steadily increasing in the last four decades—mainly driven by the needs for more renewable energies and also constantly to lower the cost of energy. The wind power nowadays plays much more important role in the energy supply system.

The state-of-the-art configurations and roles of power electronics in the wind turbine system show that the behavior/performance of wind turbines can be significantly improved by introducing more advanced power electronic technologies. By proper controls and grid regulations, it is possible for the wind farms to act like conventional power plants and actively contribute to the frequency and voltage control in the grid system, thus the wind energy nowadays is more suitable to be integrated into the power grid.

It is expected that even larger-scale integration of wind power will keep continuing in the near future. In the short term, the main focus of the power electronics technology in wind power application will be on the grid integration and compatibility of the wind power in the power system. In the long run, the challenges for lower energy cost, higher reliability, and better grid integration will push the technology developments in the WTS and enable many possibilities in respect to the power delivery structure, drive train, generator, PEC configurations, and the semiconductor devices.

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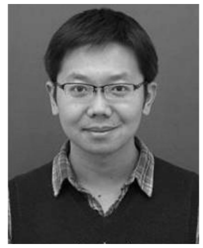

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