A Comprehensive Overview of Power Converter Applied in High-Power Wind Turbine: Key Challenges and Potential Solutions

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***Abstract*—The increasing penetration of offshore wind power generation promotes the revolution of wind turbine toward high-power application. The development of high-power wind turbine undoubtedly poses new technical challenges. This article presents a comprehensive overview for high-power wind energy conversion system (WECS) from key technique aspects, including topologies, stability, reliability, and ancillary service capability, and further investigates the key challenges and potential solutions. The various topologies of power converter applied in high-power wind turbine are first reviewed and discussed. The different semiconductor technology, including recent wide bandgap devices, and their potential contributions for offshore high-power converters are discussed. Furthermore, the potential stability issues of high-power WECS are investigated and reviewed. Also, the stabilization control strategies are discussed. Further, the reliability issue and enhancement strategies of high-power WECS are discussed, including condition monitoring, active thermal control strategy, and fault-tolerant operation method. In addition, the ancillary service capability of high-power WECS, including frequency-active power control capability and voltage-reactive power control capability, is reviewed. Finally, the future trends and potential solutions are discussed in this article.**

***Index Terms*—Ancillary service, high power, reliability, stability, topology, wind energy conversion system (WECS), wind turbine (WT).**

I. INTRODUCTION

THE wind power generation is one of the most promising renewable energy technologies throughout the world. The penetration of wind power generation in power system is being continuously increased. For instance, the European Union (EU) energy policy has a 20% renewable energy penetration by 2020. The cumulative installed wind power in the EU is increased from 80 GW in 2010 to 200 GW by 2020, and the cumulative installed wind capacity will reach up to 250 GW by 2030. Previously, the effects of wind power generation on power system are merely concerned due to the low penetration proportion of wind energy. With the increasing penetration of wind energy, the influences of wind power generation on power system become increasingly evident, which complicates the dynamic behaviors of modern power system.

In modern wind power system, offshore wind power generation is becoming a promising solution to promote the penetration of wind energy [1], [2]. The advantages of offshore wind power generation are attractive as following.

1) Offshore wind energy sources are abundant and steady, so that the annual energy production can be notably increased.
2) Offshore wind farms are commonly installed onto continental shelf to save the land resources.
3) The effects of noise and tower shadow phenomena caused by wind turbines (WTs) on consumers can be neglected.

To exploit the offshore wind energy in an efficient and cost-effective way, the application of high-power WT is being paid the increasing concerns. It is well known that the amount of wind power production can be improved as increase of power rating of WT according to wind energy conversion theory. Furthermore, the total installation cost and maintenance cost of one high-power WT are lower than a cluster of low-power WTs. Consequently, the application of high-power WT is becoming an important trend in modern wind power system. Fig. 1 shows the development trend of WT with the technique evolution of power electronics [3]. The height and volume of WT are increased as the growth of output power.

The doubly fed induction generator (DFIG)-based WT has dominated the current wind market. However, the permanent magnet synchronous generator (PMSG)-based WT [4] presents the various advantages over the DFIG configuration and it is expected to take over the future wind energy market.

1) The PMSG offers higher power curve efficiency and extended operating speed range, which maximizes energy production especially when operating at partial power. The use of a full-scale power converter leads to implement the maximum power point tracking (MPPT) along full-variable speed range, which, thus, improves the wind energy utilization efficiency.

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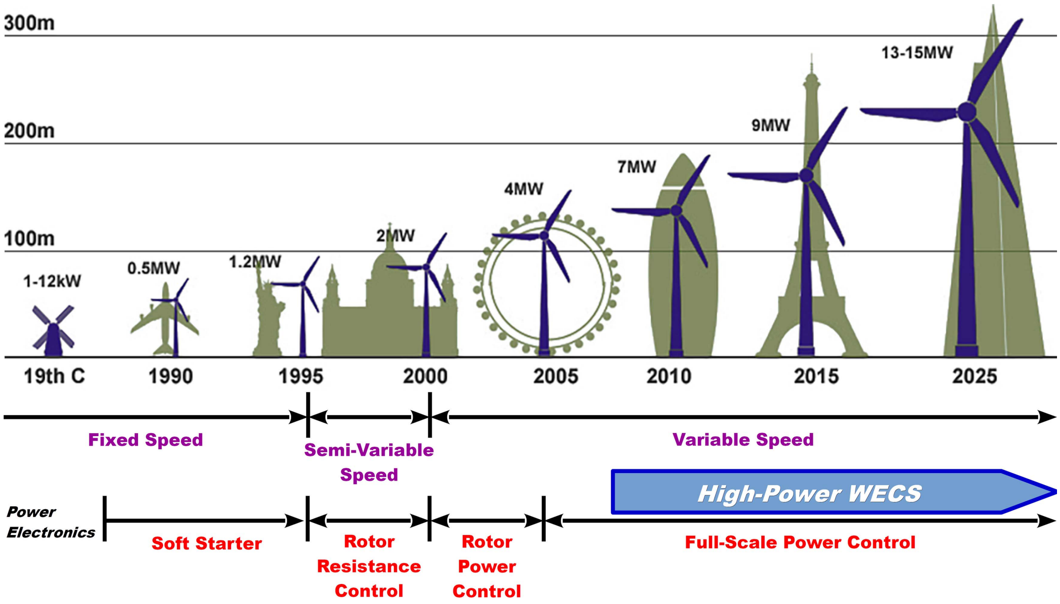


Fig. 1. The development trend of output power and heights of wind turbine [3].

TABLE I
GENERATOR SYSTEM FOR OFFSHORE WT

WT	Manufacturer	Rated Power (MW)	Gearbox	Electric Generator	
				Rated Speed (r/min)	Rated Voltage (V)
Haliade-X	*General Electric*	12	Direct Drive	7.81	3220
SG 11.0-200 DD	*Siemens Gamesa*	11	Direct Drive	8.6–9.1	820
GW175-8MW	*Goldwind*	8	Direct Drive	10.7–12.84	720
V164-10 MW	*MHI Vestas*	10	Two-stage gearbox	500	730
MySE7.25-158	*Mingyang*	7.25	Two-stage gearbox	278	690

2) The complete decoupling between wind generator and grid mitigates the effects of wind generation system on power grid. In addition, the power converter can be operated to provide grid support and improved fault ride through compliance.
3) The PMSG may improve reliability and energy efficiency of transmission system [5] due to the absence of excitation system, slip rings, and gear box, which also reduces the operation and maintenance costs.

Apart from direct-drive PMSG, semidirect-drive PMSG is also paid increasing concern [6]. The semidirect-drive PMSG, with a built-in permanent magnetic structure and an acceleration gearbox, has a relatively higher speed and fewer poles, so the weight and size of semidirect-drive PMSG can be reduced. In addition, the transportation, installation, and maintenance of semidirect-drive PMSG can be more convenient than direct-drive PMSG. The diverse generator systems are reviewed in [7] and solutions for commercialized offshore WT are listed in Table I. There is a trend toward direct-drive and semidirect-drive PMSG technology for offshore large WTs, where the reliability problem associated with conventional multistage gearbox is not convenient [8]. Therefore, the direct-drive PMSG and semidirect-drive PMSG have become an efficient, reliable and robust solution for offshore WT [9], [10]. Furthermore, the sizing of power converter system is highly related to the drivetrain technology as for rated power, voltage level, and electrical frequency. The reduced operating frequencies of direct-drive PMSG (e.g., *Haliade-X* 7.8 Hz and *SG 11.0-200 DD* 14 Hz) aggravate the thermal stress of power devices and require special consideration in the design of generator-side converter.

Power electronic converter is a critical component in WT as an efficient interface to integrate wind power into power system. A two-level back-to-back voltage source converter (2L-B2B VSC) is a well-established solution for power conversion system in commercial WT [11]. However, the conventional 2L-B2B power converter-based WECS fails to meet the requirements of high-power application [12]. The emerging high-power WECS (commonly higher than 6 MW) complicates the conventional design guideline of commercialized WTs, including power converter, transmission cable, passive components, and control system [13]. The power rating can be increased through paralleled structures to tolerate high-current values or through multilevel topologies to enable high-voltage operation. Therefore, the high-power converter is becoming a critical technology for high-power WT to achieve a reliable, robust, and cost-effective solution [14],

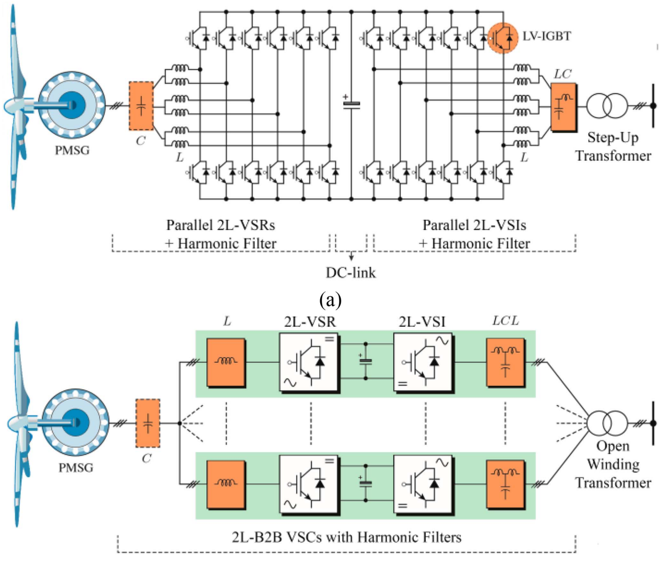
[15]. As the increasing application of high-power WT, the main technique aspects should be addressed as following.

1) *Topology of power converter:* To perform the high-power transmission, the cascaded structure with multiple paralleled power modules is required for high-power WECS. The implementation of high-power WECS in a reliable, robust, and cost-effective way is the primary technique challenge.
2) *Power devices:* The technology advancement in semiconductor devices has an important impact on high-power conversion design.
3) *Stability issue:* The instability mechanism of high-power WECS is much more complicated than conventional two-level power converter.
4) *Reliability aspect:* Reliability enhancement strategy is essential to support the long-term robust operation of high-power WECS.
5) *Ancillary service capability:* The high-power WT tends to have significant influences on dynamic behaviors of power grid, which further complicates the operation of power system. Hence, the development of ancillary service capability is essential for high-power WECS to support the robust operation of power system.

The long-term technique roadmap of offshore wind power may be altered as rapid development of power conversion technology, such as semiconductor and advanced control strategy. To investigate the potential technique challenges and solutions, this article provides a comprehensive overview for offshore wind power converter in terms of topology, power devices, stability, reliability, and ancillary services capability. Different from the previous review work regarding wind power converter in [3], [4], [9], [10], and [11], this work mainly investigates the new aspects and discusses the development trend of offshore high-power wind power converter based on the recent developments and findings, including semiconductor devices, stability, reliability, and new requirements in terms of ancillary service, etc. The aforementioned aspects are also particular concerns for future offshore WT toward high-power operation in terms of industry. The rest of this article is organized as follows. In Section II, the potential power converter topologies applied for high-power WTs are reviewed, and a comparative analysis of different converter topologies is given. In Section III, the recent advancements of power devices and the potentiality of wide bandgap (WBG) devices for high-power WTs are reviewed. In Section IV, the potential stability issues and stabilization control methods for high-power wind converter are discussed. In Section V, the reliability enhancement methods including predictive maintenance methods and fault-tolerant operation strategies are reviewed. In Section VI, the ancillary service capability of high-power WT is discussed. Finally, Section VII concludes this article.

II. POWER CONVERTER TOPOLOGIES APPLIED IN HIGH-POWER WT

In this section, the potential power converter topologies for high-power WT are reviewed with consideration of the following performance indexes.



(a)

(b)

Fig. 2. The diagram of the paralleled 2L-B2B VSCs [37]. (a) The high-power converter with common DC-link. (b) The high-power converter with individual DC-links.

1) *Reliability:* Reliability is one of essential performance indexes for high-power WECS, which are highly related with the lifetime of WT and maintenance cost.
2) *Fault-tolerant capability:* A fault-tolerant power converter can operate even in some faulty conditions. Redundant components, appropriate diagnosis, and control algorithm are required to maintain power continuity during faults.
3) *Efficiency:* Efficiency is a key performance index to evaluate the operation performance of a wind power converter. A high-efficiency topology is critical to minimize power loss in practical operation.
4) *Power quality:* The power converter can transmit power to grid with good power quality and provide grid support capability.
5) *Footprint, weight, and cost:* The power converter should be designed with high-power density to achieve small footprint, and reduce weight and cost.

A. Paralleled 2L Back-to-Back VSC System

A paralleled 2L-B2B VSC system is an attractive solution to perform power conversion for high-power WT [16], [17], [18]. The paralleled 2L-B2B VSC system allows interleaving technique by phase shifting the carrier waveforms of each VSC, so as to mitigate the current harmonic and voltage harmonic. Furthermore, the interleaving technique is able to reduce the weight and volume of passive components and cooling system [19], [20], which, thus, reduces hardware cost and improve power density of wind power converter.

Fig. 2(a) shows the diagram of the paralleled 2L-B2B VSC system with common dc-link. The imperfect symmetry in hardware results in circulating currents among multiple paralleled converters instead of flowing into power grid. The circulating current can increase the power loss of the converters, and further

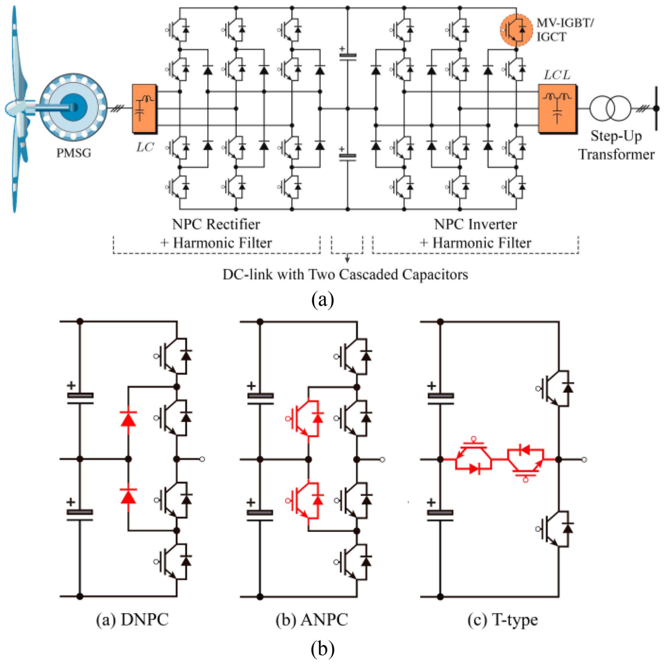


Fig. 3. The diagram of the 3L-NPC power converter. (a) The diagram of 3L-NPC-based WECS [37]. (b) The different topologies for NPC.

causes the saturation of inductors and increases electrothermal stress [21]. VSCs are connected through the filter inductor, which is able to reduce circulating current. However, additional common-mode Condition monitoring (CM) inductors are required in certain circumstances, such as interleaved operation. The added passive components increase system cost and reduce power density.

Fig. 2(b) shows the diagram of the paralleled 2L-B2B VSC system with individual dc-links. This topology improves the fault-tolerant operation capability by modularity and redundancy, where the partial power still can be delivered even if the faults of several converter modules happen. Also, the scalability and interconnection among the paralleled power converters can be simplified. Moreover, the paralleled 2L-B2B VSC system is attractive for multiphase PMSG-based WT [22], [23], [24]. Therefore, this configuration enables the optimal interleaved operation of the paralleled converters [25]. However, this configuration complicates the power control strategy, where the power sharing among paralleled power converters should be performed to ensure the system reliability and security [26].

B. Back-to-Back Neutral-Point-Clamped (NPC) Converter

A B2B NPC converter is also an attractive solution for high-power WT. Fig. 3(a) shows the diagram of the back-to-back neutral-point-clamped (NPC) converter [27], [28], where each arm consists of two traditional two-level half-bridge (HB) modules, and clamping diodes are connected to the middle point of dc-link. An NPC converter is able to generate three-level voltage waveforms with respect to dc-link neutral point, which improves the output voltage range and the harmonic filter performance. The 3L-NPC is a well-known technology that has been widely applied in high-power industrial applications. On the other hand, there are two main technique drawbacks as follows. 1) The voltage unbalance of dc-link capacitors may weaken the reliability of NPC, which should be addressed by proper modulation strategies [29]. 2) The unbalanced thermal stress caused by uneven power loss distribution among power devices [30], [31] tends to mitigate the power output capability.

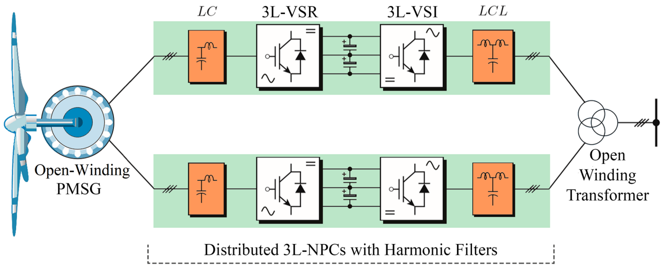


Fig. 4. The diagram of paralleled 3L-NPC converters with two power conversion lines.

Apart from the conventional NPC converter, active NPC (ANPC) converter is also developed in [32] and [33] to redistribute the unbalanced thermal stress by replacing the clamping diodes as active power devices, as shown in Fig. 3(b). The active power devices enable the new switching states that allow a specific utilization of the neutral tap to improve the distribution of thermal stresses. Hence, the output capability of power converter can be enhanced with the proper thermal balancing strategy. In addition, the T-type converter is presented in [34] and [35] for low switching frequency applications, as shown in Fig. 3(b). In the T-type converter, the upper and lower switches are paralleled with dc-link capacitors by the bidirectional switches to the midpoint. The power losses can be reduced by using active switches with low voltage rating [35]. The T-type converter is able to increase efficiency with reduced number of power devices, which, thus, decreases the hardware costs.

To increase the power rating of WECS, the 3L-NPC can be scaled up by paralleling power conversion lines [36]. Fig. 4 shows the diagram of the paralleled 3L-NPC with two power conversion lines. An open-winding transformer is applied to perform the galvanic isolation between the paralleled power conversion lines, which, thus, avoids circulating currents and reduces total harmonic distortion (THD) with interleaving technique. Furthermore, the paralleled 3L-NPC structure is able to improve fault-tolerant capability, where the WECS still can be operated even if the faults in one power conversion line happen.

C. Modular Multilevel Converter (MMC)

MMC is an attractive topology for high-voltage high-power application, which was originally developed for high-voltage direct current (HVdc) transmission [38], [39]. The MMC is a modular and scalable structure with high fault-tolerance capability. Fig. 5 shows the diagram of MMC comprising an even number of submodules (SMs) connected in series per phase. The phase arm is composed of two equal parts to generate ac multilevel output voltage. The SMs can be modeled as a controlled voltage source, and the terminal voltage of each SM

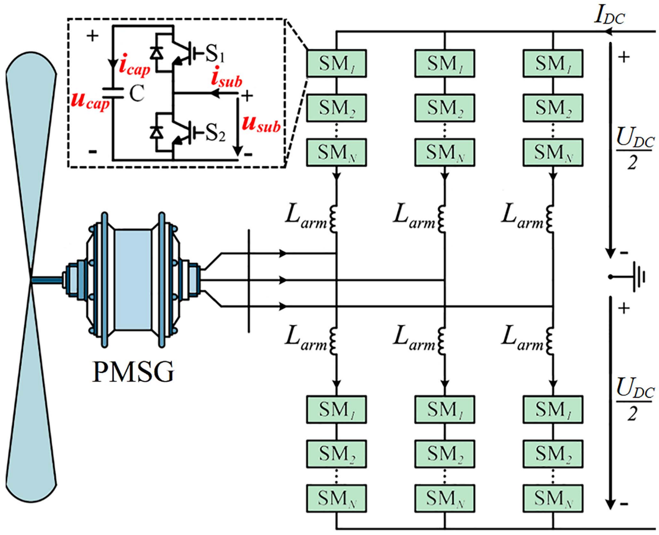
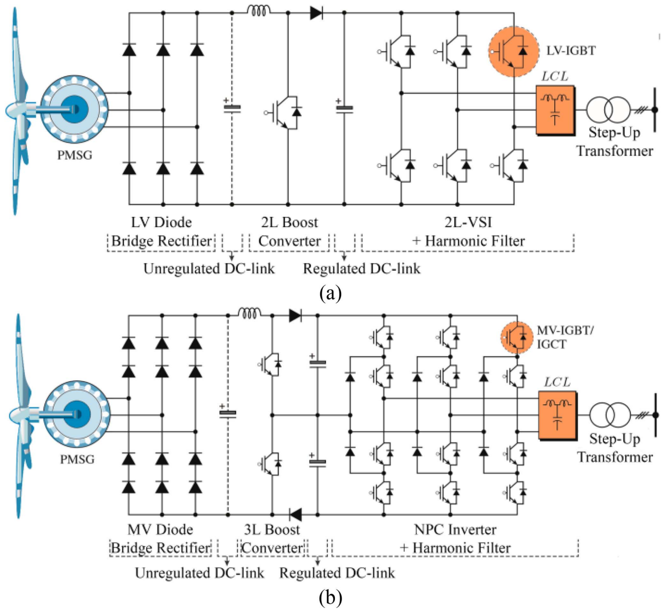


Fig. 5. The diagram of MMC connected to the PMSG-based WECS [59].



(a)

(b)

Fig. 6. The diagram of PMSG-based WECS [37]. (a) The type-4 WECS based on uncontrolled rectifier and 2L boost converter. (b) The type-4 WECS based on uncontrolled rectifier, 3L boost converter and NPC inverter.

u_{subi} can be switched between 0 and u_{cap}, as shown in Fig. 6. The output voltage can be controlled to the desired value by sorting SMs in upper and lower arms.

The MMC with different SM topologies also has been developed in [40] and [41], such as HB module or full-bridge module. The HB topology has been frequently adopted in MMC due to the low power loss and system cost [42]. The optimum number of SMs is dictated by the blocking-voltage tolerance [43], [44]. Different modulation strategies have been proposed to dynamically enable the SMs [45], [46], which are commonly divided into carrier-based algorithm and sorting-based algorithm (also known as nearest level modulation).

The mitigation of circulating current and capacitor voltage unbalance issues are main concerns to ensure the proper operation of MMC. The voltage differences among the three-phase arms generate a second-order harmonic circulating current [47], which tends to increase the power losses of power converter as well as the voltage ripple of SMs capacitor. Consequently, a circulating current controller is required to mitigate the circulating current [48]. On the other hand, the voltage across the SM capacitor always varies as the dynamic process of charge and discharge, and then, the active power is converted to ac side. Therefore, various voltage balancing strategies have been developed based on phase-shifted carriers [49], [50], and also sorting methods [51].

The MMC was previously adopted as an effective solution for high-power PMSG-based WT [52], which is a promising option for transformerless operation. Also, the MMC can tolerate high-voltage levels and enables a great reduction in average switching frequency of power device without compromise of quality of the output voltage and current [53]. To implement the reliable application of MMC in high-power WT, a complete control scheme of MMC applied in a high-power PMSG-based WECS is presented in [54], where the technical challenges including low-voltage ride through (LVRT) and the capacitor voltage ripple are mainly addressed. In [55], the fault-tolerant operation strategy of the MMC-based WECS is developed, where an online fault identification method is proposed to support the efficient and robust operation of offshore WT under different operation conditions. The application of MMC in WECS for dc offshore wind farm is investigated in [56], [57], and [58]. On the other hand, the elevated number of distributed capacitors and power semiconductors increases the complexity and hardware cost of WT, especially for full-bridge SM-based MMC.

D. Machine-Side Passive Converter

Machine-side passive converter is also an effective solution for wind power converter. In synchronous generator (SG)-based type-4 WECS, an uncontrolled rectifier with cascaded boost converter is adopted as the machine-side converter to reduce hardware cost [60], as shown in Fig. 6(a). The boost converter is able to increase the controllability of dc-link voltage and perform power factor correction. However, the usage of boost converter increases the weight and volume of WECS.

To extend the power rating of WECS, the uncontrolled rectifier can be applied by connection of diodes in series, as shown in Fig. 6(b). In this WECS, the machine-side passive converter and grid-side MMC are combined to perform the high-power transmission [61], [62]. The intermediate 3 L boost converter is connected to dc-link capacitors of NPC to enable the MV operation. The voltage rating for the active switches and diodes in a 3 L boost converter is half of the dc-link voltage. The voltage of neutral point is controlled by the 3 L boost converter during all operating conditions. The power rating of machine-side passive converter is similar with the NPC converter, but with reduced number of active switches, which, thus, is a cost-effective and reliable solution [63]. However, the machine-side passive converter also causes several drawbacks, such as the torque

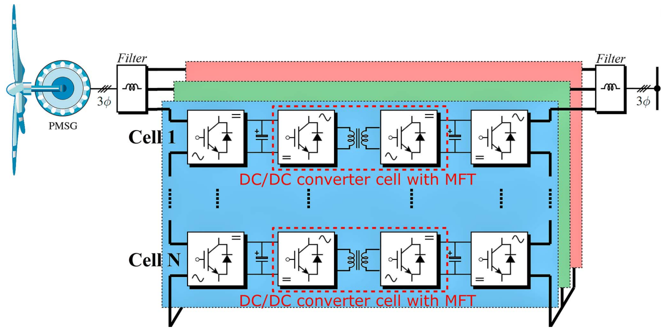


Fig. 7. The diagram of WECS based on cascaded H-bridge converter with medium frequency transformer (CHB-MFT) [72].

ripple due to harmonic distortion, and low controllability of the generator to perform MPPT.

In high-power WT, the topology with paralleled passive machine-side converters is proposed in multiphase generator with phase-shifted stator windings [64] to extend power rating. In multiphase wind generator, the paralleled diode rectifiers are connected to stator windings with 30° phase shift, which can minimize the torque ripple since the phase shift causes cancelation of 5th and 7th harmonics in the stator currents. Also, the multiwinding wind generator connected by paralleled diode rectifiers is proposed in [65] as a high-power solution, where the conversion efficiency can be obviously improved. In [66], a high-power wind converter with a paralleled unity power factor rectifier is developed to improve reliability and economic of WT. Hence, the machine-side passive converter is a competitive solution for multiphase generator-based WT in terms of reliability and economics.

E. Cascaded H-Bridge (CHB) Converter

The WECS based on the CHB converter with medium frequency transformer (CHB-MFT) is an attractive solution for high-power WT. The CHB converter is a multilevel topology by the series connection of HB power modules [67]. The B2B HB presents the similar output performance of the 3L-NPC [68], and eliminates the clamped diodes and power unbalance among the switching devices. Moreover, the capacitance value can be reduced since only half of the dc-link voltage is needed [69]. This multilevel configuration is able to increase the output voltage level and power level. As the number of output voltage levels increase, the power quality may be improved. The CHB enhances the fault-tolerant capability by the redundancy inherent to the series connection and the redundant switching state of each HB. However, the CHB needs isolated dc-link for each converter cell, which may involve open windings in generator and transformer, so as to increase the hardware cost and system volume [70]. In addition, the converter is not easy to be paralleled in order to further extend the power rating [71].

To avoid the heavy/bulky low-frequency transformer for power density improvement, the CHB-MFT converter is proposed for high-power WT, as shown in Fig. 7. The topology, which is originally proposed in European UNIFLEX-PM Project [72], is performed by the CHB structure with galvanic insulated dc/dc converters. The insulated dc/dc converter with MFT can be operated at several kilohertz, so that the weight and volume of transformer can be significantly reduced. This circuit configuration can be directly connected to the 10/33 kV power grid. The advantages of this configuration are attractive, such as high-voltage quality, filterless design, and fault-tolerance capability [73]. However, a large number of power devices as well as auxiliary components increase the hardware costs, weight, and volume of WECS.

F. Offshore Wind Farms Configurations

The configuration of collection and transmission systems plays a critical role in the cost and performance of a wind farm and has an important influence on the selection of the power converter topology. The choice of transmission technology is mainly determined by the power level and distance of the wind farm to the grid-connection point. The high-voltage alternating current transmission offers low initial cost and is a well-established technology when offshore wind farm is close to the shore. However, for distant large-scale offshore wind farms, the HVdc transmission is a more efficient and cost-effective solution [74]. The collection system interconnects all WTs of the wind farm and aggregates the generated power to a central collection point, which links to the power grid through the transmission system. In [75], a comprehensive review of collection topologies for offshore wind farms is presented.

The ac collection system, as shown in Fig. 8(a), is the standardized approach. The medium-voltage ac (MVac) collection network is formed by the paralleled WTs, whose output voltages are usually stepped-up by a transformer placed at the basement of the tower. The MVac bus is then elevated to high-voltage and rectified for transmission at the offshore substation. The preferred collection bus voltage is 33 kV, but transmitting at a higher voltage level is considered to minimize power losses [76]. However, higher interarray voltage levels may result in the bigger and expensive transformers, complicated switch gear equipment, and demanding reactive power compensation requirements.

The VSC-HVdc presents the various features that make it attractive as transmission system for offshore wind power plant [77], such as reduced footprint, decoupled reactive and active power, effective operation under weak grid, and black-start capability. In order to further reduce the cost of offshore station, the diode–rectifier unit (DRU) concept is proposed for offshore transmission system [78], [79]. A DRU comprises a six-pulse or a 12-pulse diode rectifier bridge encapsulated together with an ac transformer and dc smoothing reactance. The ac sides are connected to wind farm cluster, and the DRUs are series connected to form the HVdc link on the dc side. A DRU-HVdc collection system is shown in Fig. 8(b). The DRU-HVdc is able to reduce transmission loss and maintenance cost as a simple, robust, and cost-effective solution. Further, compared with VSC-Hdc, the volume and weight can be dramatically reduced, which decreases transport and installation cost [80]. The main technical challenge of this solution is that DRU is a noncontrollable device, so that the ac voltage must be controlled

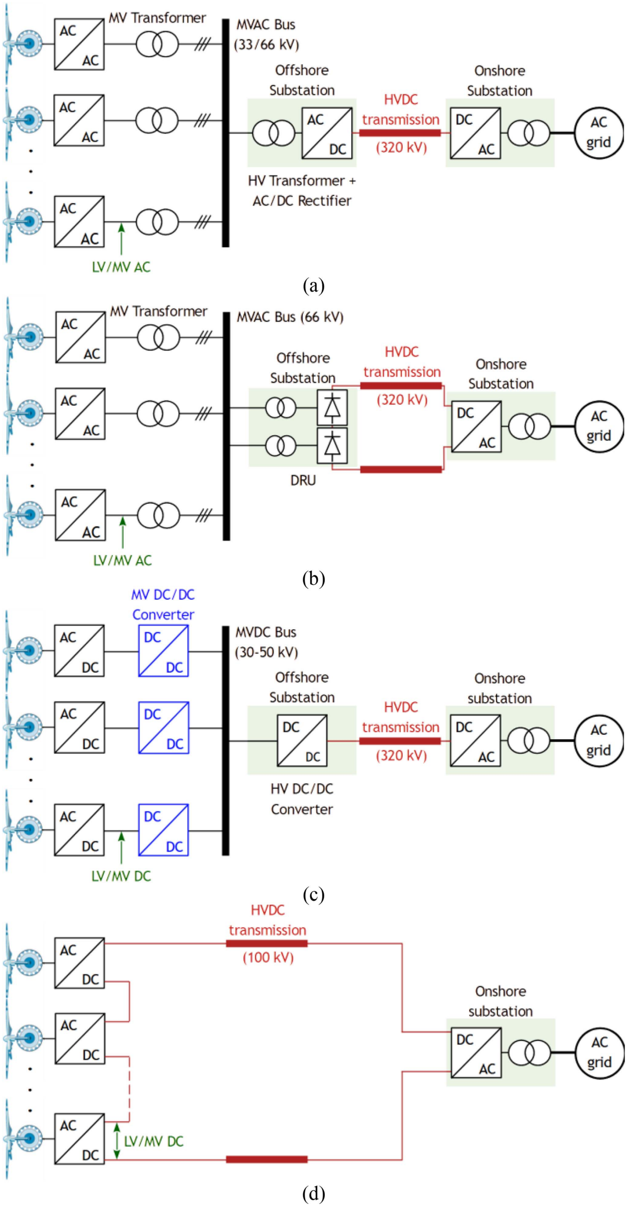


Fig. 8. Configurations for offshore wind farms with HVDC transmission. (a) AC collection. (b) DRU-HVDC system. (c) Paralleled DC system. (d) Series DC system.

by wind power converter. Moreover, additional equipment for harmonic suppression and reactive compensation is needed to meet power quality and reactive power requirements.

The novel dc collection systems have become an attractive solution to enhance the wind farm performance [81], [82]. The dc collection network presents following advantages.

1) The active power capability can be improved since the capacitive effect of ac cable is avoided.
2) The footprint and size of the offshore platforms are reduced since the bulky ac transformers can be replaced by step-up dc/dc converters.
3) The weight and cost of cabling is reduced.

The typical topologies of dc collection systems can be classified according to the connection of the WTs in parallel, series, or series–parallel (hybrid) layout. In a paralleled dc system, as shown in Fig. 8(c), the medium-voltage direct current (MVdc) collection network is formed by the paralleled WTs. An intermediate dc/dc step-up converter may be used to increase dc output voltage of WT to MVdc level. The MVdc bus is then elevated to high voltage by means of an HV dc/dc converter at offshore substation. The dc-series collection system, as shown in Fig. 8(d), increases voltage to transmission level by the series connection of WTs, which may cancel the expensive offshore platforms [83], [84]. However, the series layout presents important technical challenges for the wind power converter, such as the insulation requirements [85], [86] and the overvoltage rating [87], which is needed to handle voltage fluctuations caused by unbalanced power productions.

The dc/dc step-up converters are key components in high-power dc grid. The various dc/dc converter topologies for a wind farm application are evaluated in [88]. In [89], a 5-MW medium-voltage solid-state transformer based on dual active bridge topology is investigated. In [90], a high-power step-up resonant switched-capacitor converter for an offshore wind energy system is proposed. The topology avoids the use of medium-frequency transformers, which simplifies the design and reduces the cost of the system. However, the dc connection system is merely implemented, which presents new technical challenges as follows.

1) The different topologies of high-power dc/dc converter should be investigated to improve efficiency and reduce cost.
2) The cost-effective dc protection equipment should be developed.
3) The control issues of dc collection systems have not been fully addressed yet, and the existing grid codes and standards should be revised to contemplate all-dc wind farms [91].

The integration of large-scale offshore wind farms is a critical topic. The optimal collection and the transmission system should be selected considering the particular characteristics of the whole wind farm, such as power rating, layout, and distance to onshore. The novel dc connection systems present the technical advantages as a cost-effective solution. The paralleled topologies are similar with conventional ac collection, which thus is the first step toward all-dc wind farm [92]. However, the maturity of dc/dc converter topologies for MV applications and commercial availability of adequate switch gear equipment will decide the viability and competitiveness of dc collection system in the future. Although the dc-series collection system requires less conversion stages to reduce number of dc/dc converter, the insulation issues are especially restrictive and represent a major practical concern.

G. Comparative Analysis of Different Topologies

A comparative analysis among the different topologies is performed in Table II, where the main performance indexes and application conditions of different topologies are compared and discussed. The main aspects are summarized as follows.

TABLE II
COMPARATIVE ANALYSIS OF DIFFERENT TOPOLOGIES

	N-Paralleled 2L-VSC (Fig. 2)	3L-NPC (Fig. 3a)	MMC (Fig. 5)	3 L boost converter (Fig. 6)	CHB-MFT (Fig. 7)
Typical Power Range	N * 1.5 MW	6 MW	> 10 MW	6 MW	> 10 MW
Typical AC Voltage	690 V	3.3 kV	> 10 kV (transformer-less)	3.3 kV	> 10 kV (transformerless)
Typical DC-link voltage	1100 V	5200 V	17000 V	5200 V	2600 V
Complexity	High	Low	Medium	Low	High
Power Quality	Low	High	Very High	High	Very High
Cost	Medium	Medium	Very High	Low	Very High
Efficiency	Low	High	High	High	High
Reliability	Medium	Medium	Low	High	Low
Scalability	Easy	Easy	Very Easy	Easy	Difficult
Fault-tolerant Capability	Limited (degraded operation)	Limited	Yes	No	Yes
TRL	TRL9	TRL9	TRL3	TRL6	TRL3

1) The 2L-VSC is the widely used solution for wind power converter and the parallel connection of *N* inverters has been successfully employed to extend the power rating. The *SINAMICS W180* by *SIEMENS* [93] is a well-proven wind converter solution up to 8 MW.
2) The medium-voltage operation is promising to extend the power rating with the low output current, which increases the efficiency of the power conversion and further decreases the size of passive components, including inductors, transformer, generator, and cables.
3) The 3L-NPC power converter has an excellent tradeoff among the key performance indexes listed in Table II and is able to implement medium voltage operation by three-level outputs and reduce the requirements for filters. The *PCS6000* by *ABB* [94] and the *INGECONWIND 7.5 MW FC MV* [95] are industrial solutions of 3L-NPC power converter topology applied for high-power WECS. The paralleled 3L-NPC converter, as shown in Fig. 4, can be employed to extend power rating over 10 MW and is applicable for PMSGs with different voltage rating. It, thus, results in an attractive option in terms of reliability, flexibility, and cost.
4) The use of multiple paralleled modules may enhance the redundancy and reliability of WECS. However, the complexity of the system is increased, where the advanced control strategies are required to dynamically coordinate the paralleled power modules.
5) For WT with power rating higher than 10 MW, the MMC and CHB are potential candidates due to the high output voltage, which enables transformerless operation, and the superior expenses and complexity of these topologies can be compensated. However, the application of these topologies as wind power converter is still under research stage.
6) The complexity and hardware cost of WECS is increased with the number of power modules. Further, additional devices (e.g., control units, measuring sensors, etc.) and cabling are required to properly operate. The 3 L boost converter is a cost effective and high-reliable candidate because of the passive converter used for machine side. Despite not being commercialized for high-power WECS, this configuration is promising for future WT since it has the merits of higher power density and more optimized cost compared with other topologies.
7) The fault-tolerant capability is one of important concerns for high-power WT to ensure power continuity during faulty condition. The WECS with paralleled conversion lines can improve fault-tolerant capability, where the power converter can be operated with partial power production in the presence of fault in one conversion line.
8) To evaluate the technology maturity of the different topologies applied in high-power WT, a well-known performance index—Technique Readiness Level (TRL) [96]—is adopted, where the scale range is from 1 to 9. TRL1 indicates that the scientific research is beginning and being translated into future development. TRL9 means that the technology is proven fully in operational environment. The TRL of different topologies is evaluated by analysis based on the technique reference and real product manual [65], [93], [94], [95], which is given in Table II.

III. ADVANCEMENT OF POWER DEVICES FOR HIGH-POWER WT

The evolution of wind power converter is directly related with the development of power semiconductor devices, which have important effects on many performance indexes, such as power ratings, efficiency, reliability, and cost. The silicon-based device is a well-established solution in wind power converter. The recent advancement of WBG devices shows great potential in future high-power converter. The different semiconductor technology presents a distinct set of features. Thus, the preferred device is selected based on application requirements and the impact on the complete power converter performance. Fig. 9 shows the power rating-frequency characteristics of power devices in wind power converter. The boundaries of commercialized power devices are represented, and silicon limits are indicated by the dashed line. The potential contributions of WBG devices for high-power applications are shown.

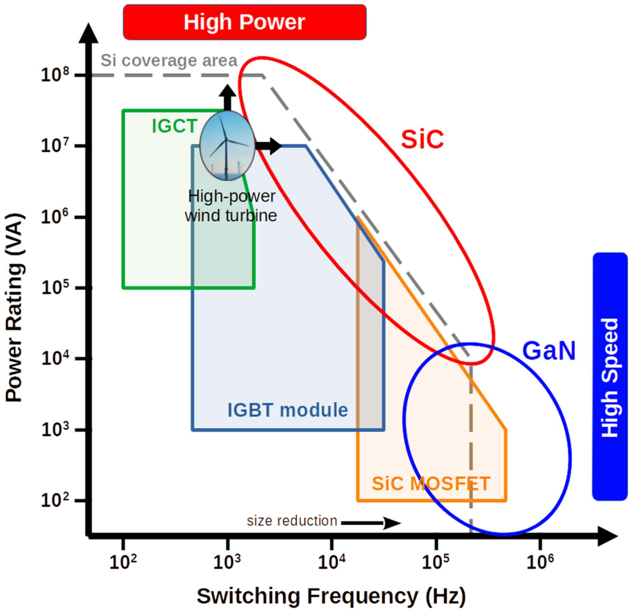


Fig. 9. Power rating-frequency characteristics of power devices in wind power converter.

A. *Advancement of Power Devices for High-Power Converter*

The key specifications of power device include breakdown voltage and current ratings, switching frequency, power density, and maximum junction temperature. In [97], a comprehensive overview about power semiconductor device is given, where the recent development of semiconductor technology is discussed. However, the application of power devices in high-power WT is merely discussed.

The insulated gate bipolar transistor (IGBT) is an effective solution of power semiconductor in wind power applications [98]. *Skiip* by *Semikron* [99] and *PrimePACK* by *Infineon* [100] are widely used commercial IGBT power modules for current WT. The research aspects of IGBT-based power devices mainly focus on the optimization of the IGBT cell to decrease the conduction loss [101], the integration of the free-wheeling-diode within a single chip to improve power density [102], and the improvement of thermal cycling capability. The development of packing technology of the IGBT is important [103]. The most common package for IGBT is the isolated module, and the alternative packaging type of press pack is developed to meet the high-power applications. The press-pack technology [104] introduces pressure contacts instead of the wire bonds and solder joints used in isolated-base modules, which further improves the thermal cycling capability, power density, and reliability [105]. In addition, the series-connection of press-pack IGBT is easier to perform, and present short-circuit failure state, which further improves the reliability. However, the clamping force distribution is a key parameter for the proper operation of press-pack IGBT, which challenges the paralleled connection operation. Hence, an external clamping system is needed, which will increase the cost.

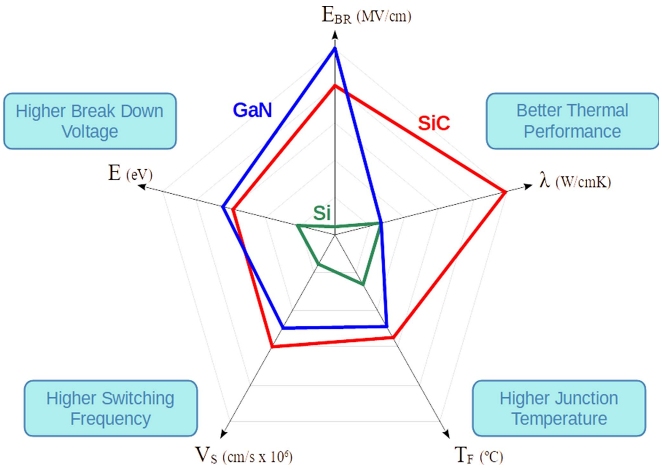


Fig. 10. Critical material properties for power semiconductor devices.

The integrated gate-commutated thyristor (IGCT) [106] is a well-established solution for high-power medium-voltage application. The IGCT is similar with thyristor in the ON-state, which may perform low conduction loss compared with IGBT, with the hard turn-OFF capability of a transistor. The IGBT is a press-pack device without bonding wire and solder failure issues, which offers reliability and further improves the load cycling capability. However, a clamp circuit is necessary to protect semiconductors from excessive current derivatives, which increases the count and power loss of components. The recent advancements in IGCT mainly focus on power ratings improvement, which is enabled by the reduction in power losses, the rise in operating temperatures and the increase in wafer size (150 mm) [107]. The IGCT-based high-power wind converter is recently developed by *ABB* company to handle up to 12-MW power conversion [94]. The high-power technology (HPT) [108] is introduced as a critical step to improve the safe operation area (SOA) of IGCT. The HPT-based IGBT incorporates an advanced corrugated p-base doping profiles, which improves the turn-OFF current capability of conventional IGCT. The bimode gate commutated thyristor (BGCT) [109] is a new design concept for reverse conducting RC-IGCT, where the thyristor and diode are fully integrated in a single structure, which enables the same silicon volume to be utilized in both GCT and diode mode. Compared with RC-IGCT, the BGCT has lower leakage current and softer diode reverse recovery. Also, the BGCT has a better thermal distribution performance, which enables the device to operate at higher junction temperatures.

The new generation of power converter based on WBG power devices, such as silicon carbide (SiC) and gallium nitride (GaN), also has been paid intensive concerns. Compared with silicon-based device, the SiC-based device has high breakdown electric field, high electrical conductivity, and high thermal conductivity. The superior material properties of WBG semiconductors allow operation at higher temperatures, higher voltages, and higher switching frequencies, which further increases the conversion efficiency. Among the possible WBG devices, SiC and GaN show the best tradeoff between the material properties and the maturity of technology [110]. Fig. 10 shows the main characteristics of different semiconductor materials in terms of operating temperature (λ, T_F), voltage ratings (E_{BR}), and switching frequency and losses (E, V_S) [111].

The SiC MOSFET is the preferred SiC power switch, as the gate-drive concepts can be adapted from the well-established solution for Si devices. High-power SiC MOSFET devices above 1.7 kV have been recently introduced to the market and present important advantages, such as the reduced switching loss and wide temperature range. In [112], the switching behavior of an SiC MOSFET is analyzed and compared with an equivalent rated Si-IGBT. The SiC MOSFET presents superior performance in terms of switching loss and demonstrated capability to operate at high switching frequency. Furthermore, the low leakage current allows SiC MOSFET to operate at temperatures beyond 200 °C, which is limited by the packaging technology. A comprehensive comparison between high-power Si IGBT modules and SiC MOSFET modules is provided in [113]. This work evaluates the switching performance of two high-power modules (1700 V/300 A) by means of experimental tests and develops the corresponding efficiency models. The results show that SiC MOSFET presents higher overall efficiency due to relatively low switching loss, although Si IGBT is still superior from the conduction loss point of view. In [114], the various commercial SiC-based devices are investigated with temperature rating up to 200 °C. SiC MOSFET modules present relatively constant switching loss and increasing conduction loss with temperature. The ON-state resistance $R_{ds(\mathrm{on})}$ has a positive temperature coefficient, which explains the increase in conduction loss as junction temperature rises. In [115], the contribution of higher gate voltage level to lower $R_{ds(\mathrm{on})}$ and its temperature dependence is analyzed.

The operation capability of SiC MOSFET at high switching frequency within a wide temperature range provides the new options in the design of power converter in terms of topology, passive components, and cooling system. Also, the power density can be significantly increased. To further extend the high-frequency operation, the soft-switching technique is proposed [116]. The soft-switching technique minimizes the overlapping of voltage and current on power device during switching transient process. Thus, the switching loss of power device is reduced so that the power converter can be operated at a higher switching frequency, which further improves power density and efficiency. However, to enable the soft-switching operation, auxiliary devices and passive components are required. These additional elements add complexity and reduce reliability of the power converter, which means an important disadvantage for wind power applications.

The SiC-based power devices pose the new challenges in terms of reliability enhancement strategies. In [117], a comprehensive review of the failure mechanisms of SiC MOSFET is provided. Furthermore, the different lifetime models are analyzed, and system-level lifetime extension strategies are reviewed. The study also addresses existing challenges and new research recommendations for SiC power converter real-time lifetime prediction and extension, such as the need to investigate failure indicators and physics-of-failure models to achieve a more accurate lifetime prediction, the use of advanced parameter estimation methods, and the need to improve the package-level thermomechanical models to enhance reliability.

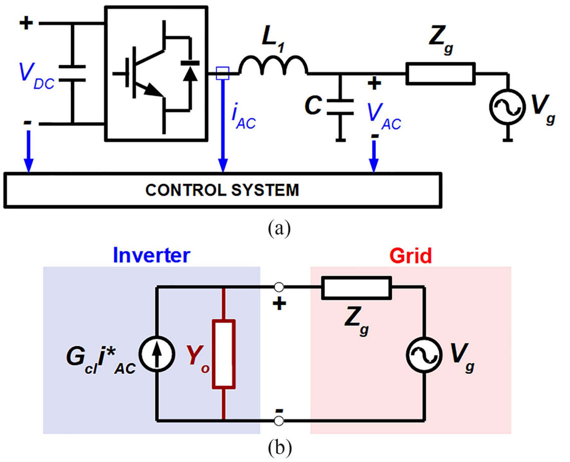
B. SiC-Based Power Converter for WT

Several papers have investigated the potential benefits of the application of SiC-based power devices in wind power converter. In [118], operation performance of the 2L-B2B power converter equipped with SiC power devices is analyzed. This work shows that an SiC-based converter offers higher efficiency than Si-based counterpart when operates at high switching frequency, which further reduces the grid-side filter inductor and the cooling system. In [119], a comparative analysis of different topologies of Si/SiC-based converter for medium-voltage WECS is given. The analysis shows that SiC-based converter presents evident advantages in terms of efficiency, power quality, and cooling system.

However, despite the promising advantages, there exist some important challenges for SiC-based wind power converters in practical operation.

1) The high cost of SiC-based devices and the manufacturing processes are still a concern.
2) The field reliability of the SiC-based converter should be further addressed. Furthermore, the lifetime models and lifetime extension strategies need to be enhanced.
3) The novel packaging technologies need to be developed to fully utilize the advantages of SiC [120]. The higher switching frequencies will demand novel interconnection technologies and optimized layout designs to minimize the electrical parasitics of the package. Further, high-temperature operation will need to incorporate advanced materials and cooling approaches to lower the thermal resistance and enhance the heat removal capability.
4) The gate driving technology should be developed to perform the high-speed switching [121]. Also, overvoltage and overcurrent protection schemes should be considered without decreasing efficiency [122], [123]. Further, the driving circuits should be designed to mitigate electromagnetic interference and support long-term operation at high temperatures.

The application of full-SiC module at high power level is still not practical due to aforementioned concerns. However, hybrid-SiC technology has been proposed as a potential approach, which can lead to a superior cost-performance ratio. A hybrid-SiC power module combines Si IGBT with SiC Schottky diode, which reduces the IGBT turn-ON switching losses and improves the overall efficiency. This technique takes advantage of the maturity level of SiC Schottky diodes and without new design of module package and gate driver. However, the high-temperature capability of SiC Schottky cannot be exploited [124]. The impact of hybrid-SiC power modules in wind power converter has also been investigated. In [125], a 2.3-MW medium-voltage NPC inverter equipped with Si/SiC modules is discussed, where the efficiency is significantly improved when SiC Schottky diodes are employed. In [126], the thermal characteristic of hybrid-SiC module is analyzed and compared with a commercial full Si module on an existing wind power converter. The use of SiC Schottky diodes enables doubling operating switching frequency, which allows a reduction of volume and weight of output filter.



(a)

(b)

Fig. 11. The simplified diagram of grid-connected VSC applied for wind turbine. (a) The simplified diagram of grid-connected VSC. (b) The equivalent impedance model of power inverter in wind turbine.

The development of compact and efficient topologies is critical for offshore wind power converter, where the optimal choice of power devices is determined by different elements, such as topology, passive components, and cooling system. In terms of efficiency and power density, the IGCT presents superior performance [127]. However, with the innovative development of IGBT, the performance gap is being filled. For the MMC topology, the IGCT presents advantages due to the reduced conduction loss and low ON-state voltage drop, and some disadvantages in terms of complexity and cost [128], [129]. On the other hand, the IGBT is more suited for CHB-MFT due to its better operation performance at high switching frequencies, which may reduce the weight and volume of the transformer. The high-frequency operation brings potential benefits, such as compact and simple topology, reduced passive components, and lower cooling requirements, so as to improve power density and conversion efficiency. Hence, the application of SiC-based devices is an inevitable trend for future offshore WT.

IV. STABILITY ISSUES AND STABILIZATION CONTROL METHODS FOR HIGH-POWER WECS

With the increasing penetration of power electronic-interfaced WTs, the oscillation phenomena within a wide frequency range have been frequently reported. Hence, the intensive efforts have been performed to investigate the root cause of oscillation phenomena or instability issues. Fig. 11(a) shows the simplified diagram of a grid-connected VSC applied for WT, and Fig. 11(b) shows the simplified diagram of equivalent circuit as a current source paralleled with output admittance (Y_o).

The previous studies [130], [131], [132], [133], [134] show that the oscillation mechanisms of WT are complex. The low-frequency instability (typically less than 100 Hz) is mainly caused by dynamic characteristics of control loops, such as dc-link voltage control loop [135], power control loop [136], and grid synchronization loop [137]. Apart from the low-frequency instability, high-frequency instability (harmonic–frequency instability) phenomena also have been reported [138], [139], which are highly related with the dynamic interaction of inner control loops with time-varying power system conditions and grid impedance. The oscillation mechanism of grid-connected inverter with *LCL* filter is investigated in [140]. The study reveals that the digital control delay has an important effect on the closed-loop stability of the current controller. Different from the conventional 2L-B2B wind power converter, the instability issues of high-power converter are more complicated, where the dynamic interaction and mutual coupling of multiple paralleled power modules in high-power WECS may trigger system oscillation behaviors due to the coupled grid impedance, as shown in Fig. 12. The analysis results in [141] and [142] indicate that the paralleled power modules may aggravate the resonance phenomena of high-power WECS. To ensure the stable and reliable operation of high-power WECS, the development of stability analysis methods and stabilization control strategies for high-power WECS is urgent.

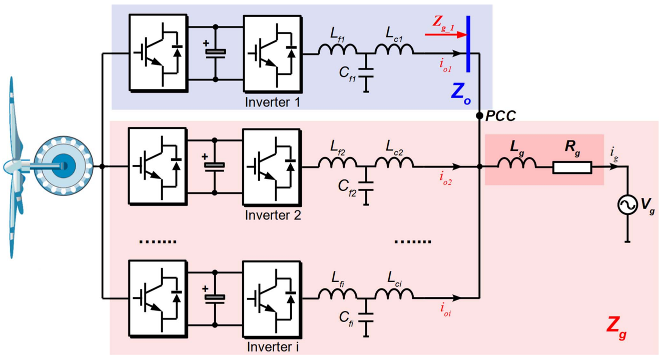


Fig. 12. The stability mechanism of high-power converter with multiple paralleled power modules.

A. Synchronization Stability

The phase-locked loop (PLL) is the widely applied synchronization solution for grid-connected VSC. The wide variety of PLL-based synchronization structures has been developed comprising the diverse research efforts, such as harmonics elimination or grid fault operation [143], [144]. Furthermore, synchronization stability has been paid major concerns [145].

The *small-signal synchronization stability* has been widely investigated and the impact of PLL on instability issue has been revealed. The influence of PLL bandwidth on stability is investigated in [146], where the high gain could cause instability of the system under weak grid conditions. Apart from PLL tuning, other modifications on PLL have been proposed to enhance the stability of wind power converter in weak grid. In [147], a virtual impedance is incorporated into PLL structure to enable the synchronization for an estimated remote voltage point, so that the stability in weak grid can be enhanced. In [148], the use of a prefilter stage integrated into the PLL is proposed to eliminate possible instability issue within PLL bandwidth.

The *transient synchronization instability* can be caused during severe grid faults, where the operating point is drastically changed, and the point to common coupling (PCC) voltage is severely altered by the network parameters and the injected current of the converter. Then, PLL should capture a new stable equilibrium point and remain synchronized with the grid. The phenomenon about synchronism loss during faults is analyzed in [149]. The different strategies have been proposed to improve transient synchronization stability [150]. The reduction of active power current during the fault is proposed in [151] to reduce the risk of synchronism loss. This method has a simple implementation, but it is deficient as purely reactive current injection may result in unstable operation. In [152], the active current reference is determined by PLL frequency error, which enables the active current control during the fault but requires an additional control loop. The PLL freeze method stops the PLL regulator when a severe fault is detected [153]. This method ensures the stable operation even under zero-voltage condition. However, as the internal states of the PLL are frozen, there is a phase-angle static error during the fault. In [154], the transient stability is enhanced based on dynamic active power balance, where the active power reference is set to the measured active power during grid faults. A proportional-integral (PI) regulator tracking the frequency deviation is also incorporated to provide positive damping effect. In [155], a similar approach based on active current reference modification is proposed to improve synchronization stability, where the frequency error control loop is avoided. However, the online estimation of grid impedance is required, which complicates the application of the method. In [156], the synchronization structure is switched to a first-order PLL by eliminating the integral gain of PLL during grid fault-occurring/clearing process, so that the transient stability can be guaranteed. In this method, the mode switching logic is set based on frequency variation detected by PLL. However, the steady-state phase-tracking error is not eliminated when first-order PLL is operated, which affects the accuracy of reactive current injection.

The influence of the synchronization loop on the stability of wind power converter is of major concern, especially during weak and faulty grid conditions. The parameterization of PLL and the active current injection profile needs to be properly readjusted to ensure the existence of stable equilibrium point during the fault. Therefore, the advanced stabilizing control strategies must be further addressed.

B. Stability Analysis Methods for High-Power WECS

To investigate the internal mechanisms of instability issues, the small signal stability analysis methods have been frequently developed, including impedance-based analysis, eigenvalue-based analysis, and passivity-based analysis.

Impedance-based stability analysis methods [157], [158], [159] have been developed to investigate the instability mechanism in frequency domain, which can assess the stability of grid-connected inverter by identifying if the ratio of inverter output impedance (Z_0) to the equivalent grid impedance (Z_g) meets the Nyquist criterion. The impedance-based analysis methods are able to identify the stability by terminal frequency response and provide insights into the effects of control loops on frequency response. Furthermore, the black-box analysis approaches are developed to perform stability assessment, where the terminal frequency response of converter is obtained by frequency scanning technique without using mathematical models [160], [161]. The various impedance-based analysis methods are developed, including *d*–*q* impedance analysis in the synchronous frame [146] and sequence impedance analysis [162]. In [163], the equivalence of the impedance models in different domains is demonstrated. Also, the impact of order-reduced models on stability analysis is analyzed. The impedance model mainly reveals the terminal frequency response characteristics, which fails to perform sensitivity analysis for identifying the participation of each state into the different oscillation modes and locate the instability sources.

Another powerful tool for the stability assessment of a wind power converter is eigenvalue-based analysis based on small signal state-space model, where the system is linearized at a certain steady-state operation point [164], [165]. Then, the stability can be predicted by analyzing the eigenvalue traces of state matrix, which is able to indicate the dynamic modes and damping characteristics of the system. Furthermore, the effects of the control loops on system oscillation modes can be evaluated. The component connection method (CCM) has been developed as a computationally efficient way to establish the state-space model [161]. In the CCM, the power system is decomposed into multiple components, which are interconnected by linear–algebraic equations to formulate the system model. The advantages of CCM are evident for large-scale power system due to good scalability. However, the prior knowledge of the system parameters and control structures is required.

The instability phenomena of high-power WECS may be aggravated by the interaction of paralleled power modules. The dynamics of the paralleled inverters could destabilize the inner control loops due to grid impedance coupling, even if each inverter is stable individually. The number of active paralleled inverters and their operating point modifies the equivalent grid impedance, which shifts the resonance frequencies and complicates the stability assessment of the whole system. Therefore, the proper analysis methods and modeling of these interactions are required. In [142], an impedance model of multiinverter system is developed to reveal the oscillation mechanism, which indicates that the interactive circulating currents among the paralleled converters can be aggregated due to the coupled grid impedance. Further, the interaction–admittance model describing the mutual interactions among the paralleled inverters in terms of a physical network admittance is established [166]. In [167], the stability of a grid-connected system with n-paralleled inverters is analyzed using the global minor loop gain, which is derived from is grid impedance and the total output admittance of the paralleled inverters. The proposed method utilizes the unified impedance-based stability criterion to assess system stability, which reduces the computation efforts compared with traditional methods. In [168], the aggregation of parallel inverters to the equivalent admittance model is discussed. Furthermore, the proposed method can predict the stability margins for system with n-paralleled identical inverters. The influence of grid-synchronization in the stability of multiple parallel inverters is analyzed in [169] and [170]. These studies demonstrate that there exists coupling among inverters admittance and discuss the effect of grid impedance in the synchronization instability, which can be mitigated by changing the PLL bandwidth. In [171], the aggregated impedance model of identical paralleled-inverter system is established in the sequence domain. This work reveals the influence of the total active power in system stability, whereas the power sharing among converters has no impact. In addition, the reactive power injection is presented as an alternative to improve harmonic stability. The effect of PCC voltage feedforward control on system stability is also analyzed.

Other critical issue to be addressed when operating high-power converters is the interaction of paralleled power modules with different switching patterns, such as operating at different switching frequencies or with nonsynchronized carriers for interleaved operation. Under these circumstances, sideband harmonics around the switching frequency can be generated by aliasing effect in the sampling process and the pulsewidth modulation (PWM) comparator [172]. The sideband harmonic resonance may be triggered due to the interaction with inner control loops. Since additional frequency component (sideband frequency) is generated, the new impedance models need to be developed for sideband frequency oscillation analysis. In [173], a multifrequency impedance model is developed to characterize the impact of sideband components. Furthermore, the impact of asynchronous carriers on the stability of paralleled inverters is analyzed and the cross-coupling effect between frequency components is depicted.

However, the small signal analysis methods are established with assumption that the system is operated at a certain steady-state operating point with nominal parameters. In realistic wind power plant, the ambient stressors, such as humidity, temperature, and vibration, have significant impacts on active and passive components, which tend to cause the parameters perturbation under long-term operation. To analyze the effects of parameter perturbation on stability of wind power converter, the stability analysis methods considering time-varying operation points are addressed in [99] and [100], where the effects of time-varying operation points caused by system parameters perturbation or ageing under the long-term operation are investigated. In [174], the nonlinear characteristic of the filter inductor and its impact on power control performance of power converter are analyzed. In [175], a Lyapunov energy function-based time-varying modeling and stability analysis method for grid-connected inverter is presented. The proposed method is able to investigate the effects of time-varying operation points caused by parameters perturbation on stability under the long-term operation. However, the generalized stability analysis methods considering parameter perturbation under practical operation conditions should be further developed.

C. Stabilization Control Method for High-Power WECS

To enhance the stability of grid-connected WECS, various stabilization control strategies, such as passive damping, active damping, and hybrid damping, have been developed to mitigate the instability phenomena [176], [177]. The switching frequency of the high-power WECS is relatively low to reduce the switching losses. Consequently, the new design guideline of digital control system would become complicated, which further changes the dynamic performances of control loops and stability regions [178]. In [179], time-delay compensation techniques are evaluated to improve the transient performance of the current control loop and enhance system stability. In [180], a virtual-resistor-based active damping technique is proposed to verify the stability of the offshore wind farm considering the effect of the transmission cable and multiparalleled converters. Furthermore, the concept of passivity is adopted to design the control system of converter, by adjusting controller parameters or adding special controllers, to mitigate resonance instability [181], [182], [183]. This concept imposes specific requirements for each individual inverter to guarantee the overall system stability [184]. In [185] and [186], the multisampling-PWM control, where the sampling and the control action is performed more than two times per switching period, is proposed to inherently reduce digital delays. The high sampling frequency operation is shown as a promising candidate for grid-connected VSCs as it enables very high bandwidths and improves the passivity. However, the conventional control methods based on certain steady-state operating points are no more effective. For high-power WECS, the development of high-performance control system is urgent. The control system should be capable for disturbances mitigation, such as time-variant grid conditions, parameters uncertainty, or time-varying passive components under the long-term operation.

To improve the operation performance of high-power converter, several advanced control strategies have been developed as the promising solutions, such as the finite control set model predictive control (FCS-MPC) [187]. In FCS-MPC-based control system, the discrete time model is adopted to predict the future behaviors of the plant and implement the optimal control actions based on predefined control objectives. Considering the finite set of possible switching states of the power converter, the optimization problem is reduced to the evaluation of all possible states and the selection of the one that minimizes the given cost function. In [37], the MPC of power converters applied in variable-speed WECS is reviewed. The FCS-MPC has been proposed as an effective solution to perform digital control of high-power converter [188], which presents several advantages compared with classical PI-based control system as follows.

1) The performance of FCS-MPC is superior in terms of dynamic response and robustness against parameter variations.
2) The modulator-free structure and the reduced digital control delay further extend the stability region of the power converter.
3) The cost function provides a flexible criterion to solve the multiobjective optimization problem in one control loop (e.g., the average switching frequency of the power converter).

The aforementioned analysis shows that high-power converter would pose new challenges on stability analysis and stabilization control strategies. The existing work mainly focuses on the stability issues of a two-level wind power converter. However, the stability analysis for high-power converter with multiple paralleled modules is merely concerned, where the new challenges about modeling and analysis are explained as following.

1) The computational-efficient modeling and analysis methods for high-power WECS with multiple paralleled modules are urgent in practical application.
2) The stability issues considering time-varying operation points should be further addressed to improve the stability of WT under long-term operation.
3) The synchronization stability analysis and enhancement method should be further investigated, and the synchronization structures must be improved to grant the power system stability during grid faults.
4) The development of advanced control strategies for high-power WECS is urgent, which is able to implement the robust and stable operation against various disturbances of system.

V. RELIABILITY ENHANCEMENT STRATEGIES OF HIGH-POWER WECS

The reliable and robust solutions are required to support long-term operation of offshore WT, even if the failure of components happens, to reduce operation cost and maintenance cost. Therefore, several efforts toward the reliability enhancement of wind power converter have been performed [189]. The reliability enhancement strategies are classified as condition monitoring and predictive maintenance, active thermal control (ATC) strategy, and fault-tolerant operation strategy. In this section, the reliability enhancement methods for high-power WECS are reviewed.

A. Condition Monitoring

Condition monitoring (CM) is an important technology to evaluate the operation status of wind power converter by measurement or estimation of electrical parameters in real time and perform the lifetime prediction for active and passive components. CM is able to capture knowledge about failure mechanisms of individual components or the integrated system, as well as data acquisition and control system, so that the health condition of wind power converter can be estimated in real time [190]. Furthermore, CM methods can predict the degradation of components under long-term operation by comparing the measured response to that predicted by a health prediction model. To enhance the reliability, it is fundamental to identify the mechanisms of component failures. In [191], the physics-of-failure of critical power electronic components is analyzed. The failure mechanisms and corresponding stressors, such as temperature swing and voltage, are listed and lifetime prediction models of IGBTs and capacitors are presented. In [192], a comparative evaluation of CM techniques for dc-link capacitors is presented. The study includes the degradation models of capacitors and summarizes the existing CM schemes for different applications, pointing out the working principle of the CM method and its main advantages and limitations. In [193], a CM method for IGBT modules is proposed. The wear-out failure mechanisms and related parameters for the CM are investigated. Then, an ON-state collector–emitter voltage measurement circuit is proposed and the several CM strategies under different operating conditions are developed.

However, the failure mechanisms of high-power converter are much more complicated. The increasing number of active and passive components also poses the new challenges on CM method, where the high number of key components and corresponding health indicators are required. Furthermore, the neighboring power modules and components hinder the measuring processes of health indicators. In [194], the conventional CM methods are reviewed and classified. This study lists the different health indicators (e.g., ON-state voltage, thermal resistance, capacitor voltage, parameter identification, etc.) used for each component, indicating the signals to be measured, and evaluates the quality of the CM method in terms of implementation complexity, accuracy, and invasion to the original system. According to the analysis in [194], the main drawbacks of conventional CM methods include: low sensitivity to degradation, limited immunity capability to noise and interferences, additional ancillary circuits for CM, calibration, and high cost. To deal with the abovementioned drawbacks, the digital twin (DT) concept-based CM methods are developed, as new emerging and promising solutions, to estimate the health conditions of the key components in power converter [195], [196], [197]. DT is a digital replica of a physical system that analytically computes the measurable characteristic outputs in real time [198]. As the physical system operates, the monitoring functions compare the measured quantities to those of the real-time DT counterparts and highlight the deviations that can indicate the incorrect system behaviors. Probabilistic models are used for the DTs to consider the uncertain elements that can affect power converter behavior, such as thermal effects or component tolerances. In addition, high sampling rates to sense certain measurements and advanced algorithms for data analysis are required. In [199], a DT-based CM method for dc/dc power converters is presented, where the DT is able to calculate the inductor current and output voltage. Further, the information from the DT and the measured data are used to identify the internal parameters of converter (including the health indicators). Thereafter, the degradation of the key components (capacitor and MOSFET) can be calculated. The advantages of DT-based CM method are attractive, since it is a noninvasive and calibration-free technique, which does not need additional hardware circuits. Therefore, the application of DT approach is a promising strategy to implement condition monitoring.

B. ATC Strategy

ATC is an effective strategy to extend lifetime of wind power converter. The principle of ATC is to dynamically change one or more temperature-related variables to reduce the thermal stress of power semiconductors during normal operation. The thermal stress is related with temperature and thermal cycling of power devices [200], which has important influences on the reliability of wind power converter [201]. Various ATC strategies have been proposed [202], such as switching frequency control [203] or the modulation index control, by the adjustment of the dc-link voltage or reactive power [204]. In ATC system, one of important steps is to estimate the junction temperature in real time, since the junction temperature of power semiconductors is difficult to measure [205]. To obtain the thermal dynamics of power semiconductors, the electrothermal models should be established to online estimate junction temperatures on the basis of electrical measurements [206] or thermal-sensitive electrical parameters [207].

For high-power WECS, the implementation of ATC is relative complicated, where the junction temperature estimation for multiple power modules is needed. Also, the advanced power sharing strategies are required to extend the lifetime of power converter according to the unequal thermal stress of the paralleled power modules [208], [209]. In [208], a lifetime-oriented power sharing strategy is developed to perform equal thermal sharing among paralleled inverters, where the temperature estimation model is developed to estimate thermal characteristics of power modules offline. In [209], an enhanced hierarchical control framework of multiple power modules is proposed to improve operation efficiency and perform system-level thermal management. In [210], the concept of power routing with unequal load sharing is proposed to balance the thermal stress, which, thus, improves the reliability and extends the lifetime of the power converter. In [211], the ATC of semiconductors is performed based on an FCS-MPC approach, because it allows to directly applying the optimal switching vector, and the precise control of thermal stress in the semiconductors can be achieved.

However, the aforementioned works mainly focus on offline temperature estimation and ATC by electrothermal model of power modules. The following aspects should be further addressed for high-power WECS: 1) The accurate online temperature estimation methods with limited application of ancillary circuits. 2) The robust ATC with parameters perturbation suppression is significant to support the long-term operation of high-power WECS.

C. Fault-Tolerant Operation Strategy for High-Power WECS

According to the practical statistics from [212], the power electronic components have the relative high failure rate in WT. For high-power converters, the number of power semiconductors and passive components is massive. Therefore, the fault-tolerant operation strategies are becoming increasingly significant to ensure the safe and reliable operation of high-power WT in the presence of component faults.

The fault-tolerant control (FTC) approaches consist of redundant strategy and nonredundant strategy. Redundant methods are implemented by adding the extra active switches or phase legs to support system operation [213] once the abnormal situations happen, which increases the complexity and hardware cost of wind power converter. Furthermore, the nonredundant methods can be performed by appropriate modifications of control strategies with minimum additional components. After the fault is detected, the system can be reconfigured to make use of the remaining space vectors, which allows the operation of the power converter with degraded performance. The nonredundant methods are able to support the fault-tolerant operation without using the extra circuits, which is a cost-effective solution. In [214], a nonredundant fault-tolerant MPC-based control scheme is proposed to ride-through the one-phase open-circuit fault in the 3L-NPC converter. In [215], a neural-network-based fault diagnosis method and system reconfiguration strategy of a 3L-NPC cascaded inverter is proposed to enhance the reliability of power supply in an electrified railway. In [216], an advanced sensorless control strategy is developed to improve the fault-tolerant capability of multiple paralleled inverters, where the proposed method adopts the measured dc-link voltage and dc-link current and SVPWM signals to reconstruct the three-phase output voltages and currents once the faults of sensors happen.

The aforementioned analysis shows that the following aspects can be mainly addressed to enhance the reliability of high-power WECS as future trends.

1) Advanced and intelligent CM method is significant, where DT approach presents attractive advantages for implementation of CM, and further benefits predictive maintenance.
2) Advanced control strategies are urgently required to perform robust ATC for high-power WECS.
3) FTC strategy in a cost-effective way is significant to maintain system operation against faults situations.

VI. ANCILLARY SERVICE CAPABILITY OF HIGH-POWER WT

The development of ancillary service capability is significant for high-power WT to support the robust operation of power system with high penetration of wind power. In this work, the potential ancillary services capabilities for high-power WT will be mainly investigated and discussed, including frequency-active power control capability and voltage-reactive power control capability.

A. Frequency-Active Power Control Capability

1) Frequency Response Characteristics of WT: Frequency instability issue of power system can be caused due to power imbalance between generation and demand [217]. Inertial response is an inherent property of conventional SG, which can provide transient power support before the action of governor within 5-8 s. Different with conventional SG, the PE-interfaced wind generator fails to automatically respond the variation of grid frequency [218], [219]. The increasing application of a PE-fed wind generator can reduce the inertia levels of power systems, which weakens the robustness of power system in the presences of disturbances. The high rate of change of frequency (RoCoF) tends to cause instability issue and safety events. Therefore, grid codes throughout the world also pose the new requirements for frequency support [220]. The wind power converter, especially for high-power WT, is required to automatically respond frequency disturbance so as to improve the robustness and safety of the power system [221].

The grid-support capabilities of WECS, such as fault-ride through, frequency regulation, and inertia emulation, are essential for the robust operation of power system with high penetration of wind power generation. In [222], the impacts of power

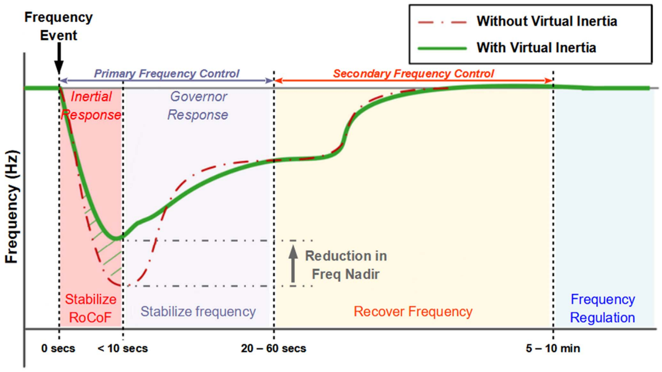


Fig. 13. The frequency response characteristics of PE-interfaced wind turbine with and without virtual inertia emulation.

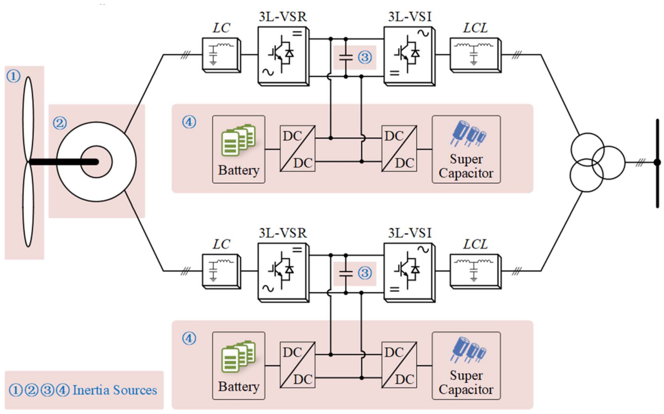


Fig. 14. The diagram of wind turbine with inertia sources.

fluctuations caused by the variable nature of wind energy on frequency characteristic are addressed. The fluctuating powers of generation and demand side tend to cause frequency deviations. The frequency events may lead to the cascading outages, or even isolation of power grid and formation of electrical islands [223].

Fig. 13 shows the frequency response characteristics of PE-interfaced WT with and without inertia emulation capability in the presence of frequency events. It can be seen that the frequency nadir is lifted, and the fast frequency restoration is performed during about 60 s with inertia emulation strategy. Therefore, the frequency-active power control capability of a high-power WT is significant for frequency stability.

2) Inertia Control Strategies of WT: The frequency support is an important capability for high-power WT, where wind power converters are equipped with inertia response and frequency regulation services. The aim of inertia response control is to extract kinetic energy stored in the WT to reduce the RoCoF. Fig. 14 shows the diagram of WT equipped with inertia power sources. It can be seen that inertia energy can be provided by rotating mass of WT, rotor of generator [224], dc-link capacitors [225], [226], or extra energy storage system (ESS) [227].

Although an extensive review on inertia emulation control strategies for wind power plants has been performed in [228], [229], their applications in high-power converters are slightly concerned. For high-power WECS, the implementation of inertia emulation strategy is more complicated and the extraction of high amount of inertia power poses new challenges. Furthermore, the several inertia supply sources present different technological attributes and possibilities of accommodation in WT. Thus, the advanced control strategies are required to coordinate the different time-scale dynamics of the inertia sources, and the power sharing strategy among paralleled power modules is required to perform the high-power inertia supports.

The different frequency regulation control schemes have been proposed for WTs [230]. The *Inertia Response Strategy* can release kinetic energy stored in rotating blades of WT. The diverse control schemes (e.g., constant additional active power, derivative frequency dependence, *power-frequency droop-control,* etc.) have been developed to emulate inertia response [231], [232]. After the inertia response stage, the WT may return to MPPT operation. During the recovery process, the output power of WTs is reduced to recover optimal speed, which might cause an undesired secondary frequency event. Furthermore, the potential problems caused by speed transients must be prevented [233]. The inertia control strategies of high-power WECS are discussed from the following aspects.

1) Power point tracking-based inertia control strategies: The virtual inertia can be emulated using an auxiliary control loop with frequency feedback, which shifts the operating point from the MPPT curve to dynamically support the grid during a frequency event. In [234], the power regulation of PMSG-based WT to enhance frequency support during transient events is investigated. The optimized power point tracking (OPPT) control scheme is proposed to provide inertial response and power oscillation damping.
2) Rotating mass-based inertia control strategies: In [235], a WT control system, which increases the active power in response to a drop in grid frequency, is proposed. The extra kinetic energy is obtained from the rotating masses of the WT, such as the rotor of generator and the blades. In [236], the Fast-Power Reverse Emulation is evaluated for type-4 WT. The inertial controller acts on the reference rotational speed to obtain kinetic energy from the WT rotor.
3) DC-link capacitor-based inertia control strategies: In [237], a dc-link voltage control strategy is proposed to provide inertia support in a PMSG-based WT. A dc-link voltage droop controller is implemented to support the grid frequency regulation. With this strategy, the virtual inertia can be emulated without increasing system cost and complexity. However, the inertia provision is limited as the energy storage of capacitors is reduced, and the lifetime performance may also be affected.
4) ES-based inertia control strategies: The use of ESS can further improve the frequency support capability of WTs. The application of ESS relieves the mechanical stress of WTs during frequency-supporting process, which is beneficial in terms of lifetime extension and maintenance costs. In [238], a hybrid ESS with battery and ultracapacitor is proposed as inertia energy sources to perform inertia emulation, which exploits the advantages of the

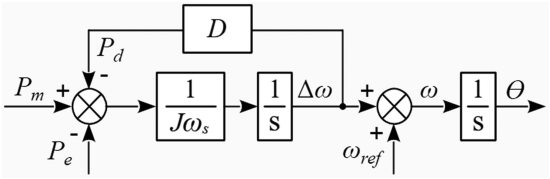


Fig. 15. Rotor swing equation of VSM.

battery (high-energy density) to compensate the long-term power response required by frequency fluctuation, and the ultracapacitor (high-power density) is adopted to provide the short-term power for inertia emulation. In [239], a type-4 WT equipped with minute-level ESS is studied. With minute-level energy capacity, the WT is able to compensate the power fluctuation of the wind generation and to provide dynamic grid support. Furthermore, frequency support under low wind speed is enabled and the impact of rotor speed recovery can be mitigated [240]. In addition, the coordinated operation of diverse categories of ESS, each of them with different response timeframe, can enhance the overall frequency support performance [241].

The *deloading-control* technique ensures the inertia reserve margin by controlling the WT at a reduced power level. This way, an amount of spinning reserve active power is booked to address frequency contingency. To release the power reserve margins, the rotor speed, and pitch angle can be controlled based on wind speed conditions. The pitch angle controller is mainly applied above rated wind speed when the rotor speed required for deloaded operation may exceed functional limits [242]. However, dynamics of pitch angle are slow, which limit the inertia response, and the frequent adjustment may increase the mechanical stress and fatigue of the WT. Although the deloading technique implies a certain percentage of energy loss, the capability of WTs to provide inertia support during a short period is enhanced and the impact on the grid during recovery period is minimized [229].

3) Inertia Control By Virtual Synchronous Machine (VSM): The VSM is a control strategy applied to the power converter to emulate the dynamic characteristics of SG, as shown in Fig. 15. The various VSM control strategies with different models of SG have been developed. The different equivalent models of the machine and the specific characteristics, covering both mechanical component (the swing equation) and electrical component (armature windings, field windings, and damping circuits), can emulate different dynamic performances.

In [243], the VSM control schemes are reviewed and classified according to the order model of the VSM implementation. In [244], the VSM control algorithms are analyzed and categorized considering the external ESS. Furthermore, the viability of VSM algorithms under abnormal operation is studied by means of discrete-time simulations. However, this work fails to address the implementation of VSM in high-power WT. In [245], the application of VSM control on WTs is reviewed. Several works regarding the VSM-controlled WTs are discussed from the following aspects:

1) different control schemes with and without ES;
2) performance analysis under different grid conditions;
3) effectiveness on the frequency control.

This study emphasizes that further research work is required, such as verified comparisons between different schemes, in terms of stability and performance in frequency control.

The application of VSM on WTs is not straightforward since the control structure is drastically changed and further research is needed. Therefore, other control strategies have been developed to enhance the inertia emulation of WTs. In [246], the *virtual capacitor control* combines dc-link inertial control and rotor speed frequency. Since the inertia provided by dc capacitor is limited, the proposed strategy exploits rotor kinetic energy to supply larger virtual capacitance and avoid excessive dc voltage deviation. The inertial response characteristics of WT are determined by power control and synchronization loops [247]. Therefore, inertial emulation based on the PLL parameterization is also investigated [248]. The inertia PLL presented in [249] augments the typical PLL structure with an inertial control loop and a damping control loop to emulate the frequency response characteristics of the SG. The PLL-based inertia control methods can be performed without severe modifications and extra outer control loop, which further results in a faster inertial response. However, the dynamic response of phase acquisition is slowed down, which may affect fault ride-through (FRT) capability and concern the coupling effects among WTs.

In summary, the application of inertia control methods in high-power WT poses the emerging challenges as follows.

1) The power sharing control strategies are necessary to properly distribute the inertia power among paralleled power modules.
2) The different frequency control strategies should be revised to ensure the power-coordinated control between WTs and provide the best frequency support at wind farm level.
3) The application of ESS is necessary to implement the transient high-power release. The optimal design guideline and cost optimization method for high-power WECS with ESS should be further addressed.
4) The different VSM control schemes should be further investigated in terms of stability and dynamic performance under different grid conditions, such as weak grids, unbalanced grid, and grid faults.

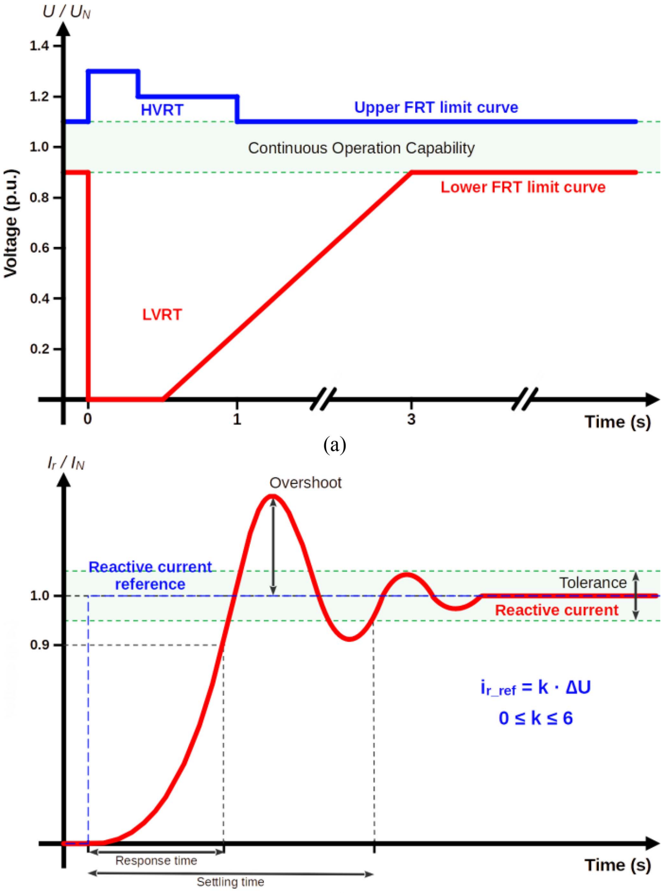
B. Voltage-Reactive Power Support Capability

1) Reactive Power Characteristics of WT: Voltage stability is related to the capacity to maintain steady voltages at all buses in the power system, which is essential to ensure the reliable delivery of the power to the transmission network. Each grid presents different voltage changing characteristics depending on the loading, the short-circuit power, and the reactive power demand of elements in the transmission system, such as cables and transformers. In steady-state operation, the reactive power control consists of capacitive or inductive current injection in response to PCC voltage deviations. The reactive power requirements are typically defined by the PQ-profile and the

UQ-profile, which determine the reactive power requirement (Q) as a function of the active power (P) and the PCC voltage (U). The typical requirement of grid codes is rated active power operation between 0.9 power factor cap./ind. at ±0.1 per unit rated voltage. The grid codes are the technical specifications emitted by the transmission system operators, which provide sets of regulations according to each country requirements. A complete review of European grid codes for wind farms is presented in [250].

2) FRT Capability: Reactive power support capability is of importance for modern WT. Grid codes require the WT to stay operational and remain the ride-through capability under a temporary voltage fault [251], [252]. Low-voltage ride-through (LVRT) capability refers to the capability of the WECS to remain integrated into the utility network in the case of low-voltage events, where the reactive power control is required to provide the PCC voltage support by capacitive or inductive current injection. The requirements about reactive current injection are specified using voltage–time profiles and the ride-through operation must be accomplished within 30 ms in case the grid voltage falls below the 90% value, as it is defined in the German grid code VDE-AR-N 4110/20 [253], [254]. An overview about LVRT methods of grid-integrated wind generator has been performed in [255], [256], including dc-link chopper, ESS, and FACTS device. In previous works, the LVRT capability of conventional WT is addressed, but the LVRT capability of high-power WT is merely discussed. An advanced LVRT control strategy is developed to enhance the ability of reactive power support of DFIG-based WT during serious voltage dips in [257]. The wind energy continuously captured by a WT during a fault can be stored into rotor as inertia energy, which will be released back to the grid after fault clearance. In [258], a predictive control scheme is proposed for the LVRT enhancement of NPC converter-based PMSG WTs, where the turbine–generator rotor inertia is adopted to store the surplus energy during the grid voltage dips. The proposed predictive control is able to provide a fast response time to switch from normal operation to LVRT operation during the grid faults.

With the increasing share of wind power in the power supply, the new challenges have appeared. In this context, the FRT capability in terms of overvoltage is an increasingly discussed issue in the development of modern grid codes. Temporary overvoltage may be caused because of load shedding, phase-to-earth faults, dynamic load variations, and huge transmission line capacitances. In order to avoid critical situations caused by overvoltage, the high-voltage ride-through (HVRT) capability has become a crucial aspect. Therefore, modern grid codes include the corresponding requirements to assess the stability of the power system and the WT must be able to ride-through high-voltage conditions and provide inductive reactive power to the grid in the case of voltage boosts. In [259], a control strategy based on the modulation voltage regulation is proposed to enhance the HVRT operation of a PMSG-based WT. This study uses a closed-loop control of the maximum output voltage of the grid-side converter (GSC) to generate the inductive reactive current reference, and the results show a robust operation against overvoltage. However, only the power converter voltage limitation is considered, and issues related to voltage support contribution and grid code compliance are avoided. In [260], a control strategy of FRT for a medium-voltage three-level full power WT is presented. This control proposes a variable dc-link voltage reference and the use of overmodulation to improve the controllability of the GSC during HVRT. Furthermore, the machine-side power is limited during the fault to reduce the burden of the chopper circuit. Also, the control method for neutral-point balance is proposed, which eliminates the zero-level to inhibit the large fluctuations of the neutral-point under grid faults. Nevertheless, the grid compliance in terms of reactive current provision is also overlooked. In [261], the HVRT capability of the PMSG-based WT is improved with the use of a supercapacitor energy storage unit. The supercapacitor is connected in the dc-link to store the excess energy between GSC and machine-side converter during the voltage swell. This way, the GSC is released from active power regulation and the reactive current provision is enhanced during voltage swell.



(a)

(b)

Fig. 16. Fault ride-through (FRT) requirements. (a) FRT limit curve for the voltage curve at the network connection point. (b) Procedure of reactive power supply during LVRT event.

Fig. 16 shows the standard FRT requirements for WT. In Fig. 16(a), the operation capability areas are presented for both HVRT and LVRT, where the WT is required to dynamically support the grid voltage during the fault. Fig. 16(b) shows the current injection profile during LVRT event. The reactive current must reach 90% of its designated value within 30 ms (response time) and its tolerated stationary value within 60 ms (settling time). The reactive current reference is defined proportional to the grid voltage deviation *($i_{r\cdot\mathrm{ref}} = k\,\Delta U$)*, where the proportional gain is defined by grid operators in the range of $0 \leq k \leq 6$. Although LVRT is state of the art among the manufacturers of WT generators, the precise reactive current determination and the different control strategies are subject to further investigation. The HVRT has not been extensively researched yet. Furthermore, the conventional reactive power control strategy is not effective for high-power WECS with multiple paralleled modules, where the reactive power should be properly shared among paralleled modules by reactive power sharing strategy.

The application of protection circuit is also an effective solution to keep the converter safe from the problems caused by voltage dips, where the unbalanced power between the generated power and power injected into grid is normally dissipated by dc chopper in dc-link [262]. For the case of DFIG-based WT, the higher rotor currents appear during severe grid fault transients and the crowbar circuit is proposed to protect power converter [263]. The activation of crowbar circuit shorts rotor windings, which restricts the system controllability and, thus, complicates the FRT compliance. Some advanced control strategies have been developed to enhance the LVRT in DFIG-based WECS without the installation of auxiliary hardware. In [264], a virtual damping flux-based control strategy is proposed to reduce rotor overcurrent during transients of grid voltage dip. In [265], the rotor-side converter is controlled to emulate an inductance when a grid fault is detected. This work shows that rotor current and rotor voltage can be effectively controlled with the proper value of the emulated inductance. In [266], a crowbarless LVRT strategy based on flux linkage tracking is developed. When a voltage dip is detected, the controller is switched to LVRT mode, where the control-winding flux linkage vector is controlled to track power-winding flux linkage. The analysis shows that the current peak and torque ripple can be limited during grid fault. The LVRT strategies without hardware protection increase system reliability and reduce hardware cost. However, they are limited by maximum output voltage of rotor-side converter, especially during severe grid faults and asymmetrical faults. Furthermore, the fast and seamless transition between control modes is essential in control system [255].

The application of ESS, such as battery and supercapacitor, is also an effective solution to mitigate power fluctuation and enhance FRT capability. In [267], an advanced FRT technique for PMSG-based WT is proposed, where a hybrid control scheme for ESS and dc chopper is developed to perform FRT and mitigate power fluctuation. The dc-link voltage is stabilized by ESS while the GSC is exploited as a reactive power compensation device to inject reactive power current into grid for assisting in grid voltage recovery.

3) Grid-Forming Control: The power electronic-dominated power systems are subject to disturbances due to the absence of rotating inertia. Hence, the active grid support strategy, such as grid-forming control, is presented to enable stable operation [268]. Grid-forming units are controlled as a voltage source with a link impedance. Thus, the power flow is determined by the voltage imposed by the VSC, the PCC voltage, and the use of a virtual admittance. In addition, grid-forming control can properly overcome the cases of system blackout and is compatible with conventional grid-feeding schemes. The various grid-forming control schemes are reviewed in [269], including *droop-based grid-forming control* [270], *power synchronization loop* [271], *virtual synchronous machine* [243], and *direct power control (DPC)* [272]. In [273], it is proved that power system with 100% inverter-based generation can be stabilized when a portion of the power converters with grid-forming control is applied. In [274] and [275], an overview of different configurations for black start provision by offshore wind farms is presented. Black start is the procedure to restore the electrical network from a total or partial shutdown without relying on the external transmission network. Offshore wind farm can be exploited to provide a fast and environmental-friendly black start service and contribute to grid restoration. Wind power converter can be enabled by grid-forming control strategy as a controlled voltage source to provide black start service. The existing works emphasize that grid-forming control, different from conventional grid-following control model, is a promising control technology for offshore wind power converter to provide grid support service, where the different schemes require a further comparison of its performance and inertia emulation capability.

In summary, the increasing application of high-power WT poses the new emerging challenges in voltage-control and reactive power support strategies as follows.

1) The implementation of reactive power support capability for high-power WT is more complicated, where the existing voltage support control schemes are based on a conventional WT. The development of advanced reactive power sharing strategies for high-power WECS is important to avoid the circulating current among paralleled power modules.
2) The design and sizing of the power converter is more complicated because of the required reactive power capability. Furthermore, the application of protection circuit, such as dc chopper circuit, and the accommodation in high-power WECS with paralleled modules in an efficient and cost-effective way is an important concern.
3) ESS is becoming a key component for FRT and power smoothing. The optimal design and sizing method of wind power converter equipped with ESS is an important concern.
4) The future high-power WECS will be responsible for voltage control. The intelligent and coordinated application of grid-forming control strategies are required to stably operate the power system.

VII. DISCUSSION AND FUTURE TRENDS

The growth of offshore wind power generation promotes the application of high-power WT, which also poses new technical challenges for high-power WECS. This article presents a comprehensive overview for high-power WECS in terms of topologies, stability, reliability, and ancillary services, and further investigates the key technique challenges and potential solutions. The future trends and solutions for high-power WT can be summarized as the following aspects.

1) *Converter topology:* The efficient and cost-effective topology for high-power WECS is important. The optimal topology of WECS can be specified according to power ratings. For the power range for current offshore WECS up to 15 MW, the power conversion can be implemented by multiple conversion lines composed by paralleled 2L-VSC and 3L-NPC converter. The 3L-NPC converter has an excellent tradeoff among the key performance indexes. For WT with higher power rating, the MMC and CHB are qualified candidates due to the high output voltage. Furthermore, the development of WBG power devices presents enormous potential in future high-power conversion structures.
2) *Stability issue:*
    a) The computational-efficient and high-accuracy modeling and analysis method for high-power WT is urgently required.
    b) The stability modeling and analysis methods considering time-varying operation points, nonlinear dynamics, and parameters perturbation are essential, which can contribute to parameters optimization and robustness enhancement under long-term operation.
    c) Advanced control strategies, such as MPC and FTC, are becoming promising control methods to improve the overall operation performance of high-power WT.
3) *Reliability issue:* Reliability is one of essential concerns for high-power WT.
    a) Intelligent and predictive maintenance strategies are becoming increasingly important, especially for offshore high-power WT due to expensive operation and maintenance costs. The digitalized CM method is a promising direction for online diagnostics.
    b) The ATC strategies (e.g., power routing) are required to extend lifetime of the wind power converter by means of the reduction of the thermal stress of power semiconductors during long-term operation.
    c) The fault-tolerant operation strategies are significant to ensure the safe and reliable operation in the presence of component faults. The nonredundant methods are the cost-effective solution due to the absence of additional components.
4) *Advanced ancillary service capability:* The effects of wind power generation on power system are becoming increasingly evident. Hence, the advanced ancillary service strategies, such as frequency regulation and reactive power support, are significant for high-power WT to support the robust operation of power system. a) Different with the conventional low-power WT, the development of frequency-active power control strategy is more complicated. The power sharing strategy should be developed to perform the optimal power sharing among paralleled power modules of high-power WECS. b) The advanced reactive power-sharing strategies for high-power WECS are important to avoid the circulating current among paralleled power modules.
5) *Grid-support and grid-forming technology:* The integration of grid support capability, such as inertia emulation, and black start, into offshore WT is an important trend. A wind power converter enabled by grid-forming control is a promising solution to provide grid support service. The availability, stability, and economics of grid-forming control strategies in different converter topologies should be further investigated. The optimal design methods of grid-forming control delivering multiple support services, such as stabilization control, inertia emulation, and black start, should be further developed.

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