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Power electronics in wind generation systems

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ABSTRACT

The integration of wind power into the power system has been driven by the development of power electronics technology. Different from the conventional rotating synchronous generators, the wind power is interfaced with static power converters. The role of converter-interfaced wind power generators in the future power system is worth rethinking, from passively following the power system to actively participating in its regulation. Here we first review the achievements of wind energy development in the past decades. Then we highlight the role of power electronics for wind power systems including their advanced control and issues from the power system-level perspective relative to the emerging requirements on supporting the future sustainable power systems. Then, we revisit some ongoing pilot projects and demonstrators in Europe to identify the current research focus of wind power systems. Finally, the future development trends to enable a better integration of wind power energy are discussed.

Introduction

The global energy landscape is undergoing a profound transformation as traditional fossil fuel-based power systems encounter a confluence of challenges ranging from fuel scarcity[1] and environmental pollution[2] to the urgent realities of climate change[3]. Beyond these challenges, the conventional synchronous generator-dominated power grids has demonstrated its limitations in delivering electricity in a manner that is flexible, efficient, and intelligent due to the centralized hierarchical structure, heavy mechanical components, and slow regulation[4]. The need of the hour is a paradigm shift towards sustainable energy sources that can not only alleviate the environmental burden but also provide a resilient and flexible energy infrastructure. Renewable energy, particularly wind energy, emerges as a promising solution to bolster the sustainability of power systems[5]. Harnessing the wind energy has the potential to contribute significantly to the generation of clean and low-carbon electricity[6]. However, the integration of wind energy into existing grids has proven to be a formidable challenge as the penetration level increases[7]. The inherently intermittent and non-dispatchable nature of wind energy poses operational complexities that conventional approaches struggle to manage. Even sophisticated wind speed forecasting techniques[8–10] fall short in addressing the inherent oscillatory characteristics that can disrupt power grid operations. Power electronics conversion technology - a transformative approach that holds the promise of integrating a substantial proportion of wind energy into power grids while circumventing the drawbacks associated with its intermittency[11–13]. The wind power technology with power conversion system has evolved from its early 21st-century beginnings into a diverse array of sophisticated technologies tailored to meet a spectrum of requirements[14]. Its role in power systems is gradually changing from passively following the power systems to actively participating in the regulation[15,16]. Despite its potential, the power conversion system remains an underexploited asset within the realm of wind power technology.

The power conversion system offers a means to effectively channel wind power into the grid, enabling a grid-friendly integration and promoting the replacement of conventional fuel-supplied synchronous generators[17–19]. The wind power technology with power conversion system yield a spectrum of environmental and economic advantages, encompassing reduced fossil fuel consumption, alleviated carbon emissions, and mitigation of global warming[20]. It also promise heightened energy efficiency, reinforced power grid security, and diminished electricity costs[21]. In addition, the inherent flexibility of the power conversion system engenders intellectual and high-quality services, fostering an enhanced quality of life.

Nonetheless, the journey toward realizing the power-electronics-based wind integration into power grids for sustainability has obstacles rooted in hardware and software limitations, as well as industrial challenges encompassing cost, reliability, energy market. Encouragingly, advancements in power semiconductor devices and converter topologies are offering wind energy integration with heightened power capacities, reliability, and efficiency[22,23]. The deployment of advanced control strategies with the help of digital technology further improve the stability and optimal performance[24–26]. Moreover, the convergence of positive wind energy policies, dynamic market landscapes, and the pressing imperatives posed by energy and climate crises collectively underscore the opportune juncture for achieving high-penetration wind energy integration[27].

In this Review, we examine the evolution of wind power technology with power electronics integration. We explore the development of wind generator, technical requirement, and grid codes. Then we examine the power electronics in wind generation systems. We also highlight progressive advancements in the operation, control, and application in power systems of wind generation systems. Finally, we outline key challenges that need resolution to realize the full potential of wind power systems.

State-of-the-Art of Wind Generation Systems

Among various renewables, the hydropower bears the largest share (more than 1/2) of electricity generation worldwide. Nevertheless, in the past decade, wind and solar generation have been the fastest growing renewables compared to others. Specifically, the wind generation accounts for 24.7% until the end of 2022, which is much larger than the solar generation accounting for 15.5% (Fig. 1a)[28]. Meanwhile, as the rapid development of power electronics technology, the wind power generators have been through a substantial technological transformation over the past few decades (e.g., from fixed-speed low-power wind turbine generators to various-speed high-power wind turbine generators)[17,19,29]. In this section, the development of wind generation systems will be reviewed and the Grid Code requirements for grid integration will be discussed briefly.

Development of Wind Generation Systems

Wind generation systems harness the power of the wind to convert kinetic energy into electricity, making wind one of the most popular renewable energy sources[30,31]. In wind generation systems, the wind turbine (WT), the electrical machine, and the grid-interfaced converters are three key components, which have been developed respectively in the past few years[32,33]. The WT is used for converting the wind energy into mechanical energy. Currently, WTs with larger capacities and longer rotor blades have become more prevalent (Fig. 1b). The capacities of WTs have been increased from kilowatt (kW) to megawatt (MW) level[34]. Meanwhile, the role of WTs has become active contributor instead of a troublemaker for the power grid[13].

The electrical generator for the power grid and the grid-interfaced converters are usually used for converting mechanical energy into electrical energy and further transfer it into the power grid. As the development of the power electronics, the power electronics converters are increasingly equipped on wind generation systems[35,36]. For example, back-to-back converters are equiped on both type-3 and type-4 WT generators. Since the converters are fully controlled, more flexible control strategies can be used to improve the performance of the WTs.

Moreover, due to the intermittent characteristics of wind resources, WTs are often deployed in groups in a wind farm. Besides, wind farms are strategically located in areas with consistent and strong wind resources, such as coastal regions, plains, or high-altitude locations[37]. By clustering multiple turbines together, wind farms achieve higher overall energy output and improved grid integration. The on shore and offshore wind energy capacities are increasing year by year (Fig. 1c). Until 2022, the global capacity of onshore wind power is around 830 GW, while the global capacity of offshore wind power is around 65 GW. As the installation of onshore wind farms tends to be saturated, offshore wind farms have more potential in the future[38–40].

Since the wind energy is an intermittent power source due to the fluctuation of the wind speed, effective grid integration is essential to balance electricity supply and demand. Therefore, wind power generation is expected to play a more dynamic role in grid regulation, necessitating compliance with rigorous grid codes, which will be explored in the subsequent sections.

Challenges Faced by Wind Power Industry

Although the wind power industry has made significant progress in recent years, it still faces several challenges. These challenges are crucial to address to make wind power more reliable, efficient, and cost-effective[41,42]. Here are some key challenges and examples in the wind power industry:

1. Offshore power delivery: Transmitting electricity generated from offshore wind farms to onshore grids is a significant challenge, because offshore wind farms are often located far from the shore, which makes the installation of undersea cables expensive and technically complex. In addition, the long-distance AC transmission requires plenty of reactive power compensation on the offshore substation, which also increases the cost. To address this issue, HVDC transmission has been developed by industry, such as Hitachi Energy, Siemens Energy, and General Electric (GE). However, accompanied by HVDC power transmission, the high-power AC-DC and DC-AC converters bring some new challenges, such as power losses, stability, reliability, insulation, and protection issues of power electronic systems.

2. Stability and oscillations: The converter-interfaced wind turbines usually rely on a PLL to lock the phase angle of the grid voltage to achieve synchronization. As the wind power penetration increases, the grid strength, typically described by the short circuit ratio (SCR), will be reduced dramatically. Then, the PLL-based grid-following wind turbine may have small-signal and transient stability challenges[43,44]. For example, in 2017, sub-synchronous oscillation events occurred in South Texas, USA, where the oscillation frequency was 22-26 Hz. In 2019, 9-Hz oscillations were observed in Great Britain's power system, and weak grid oscillations were later identified as the reason. In 2021, 8-Hz oscillations were observed in Scotland, where there is high penetration of wind farms[45].

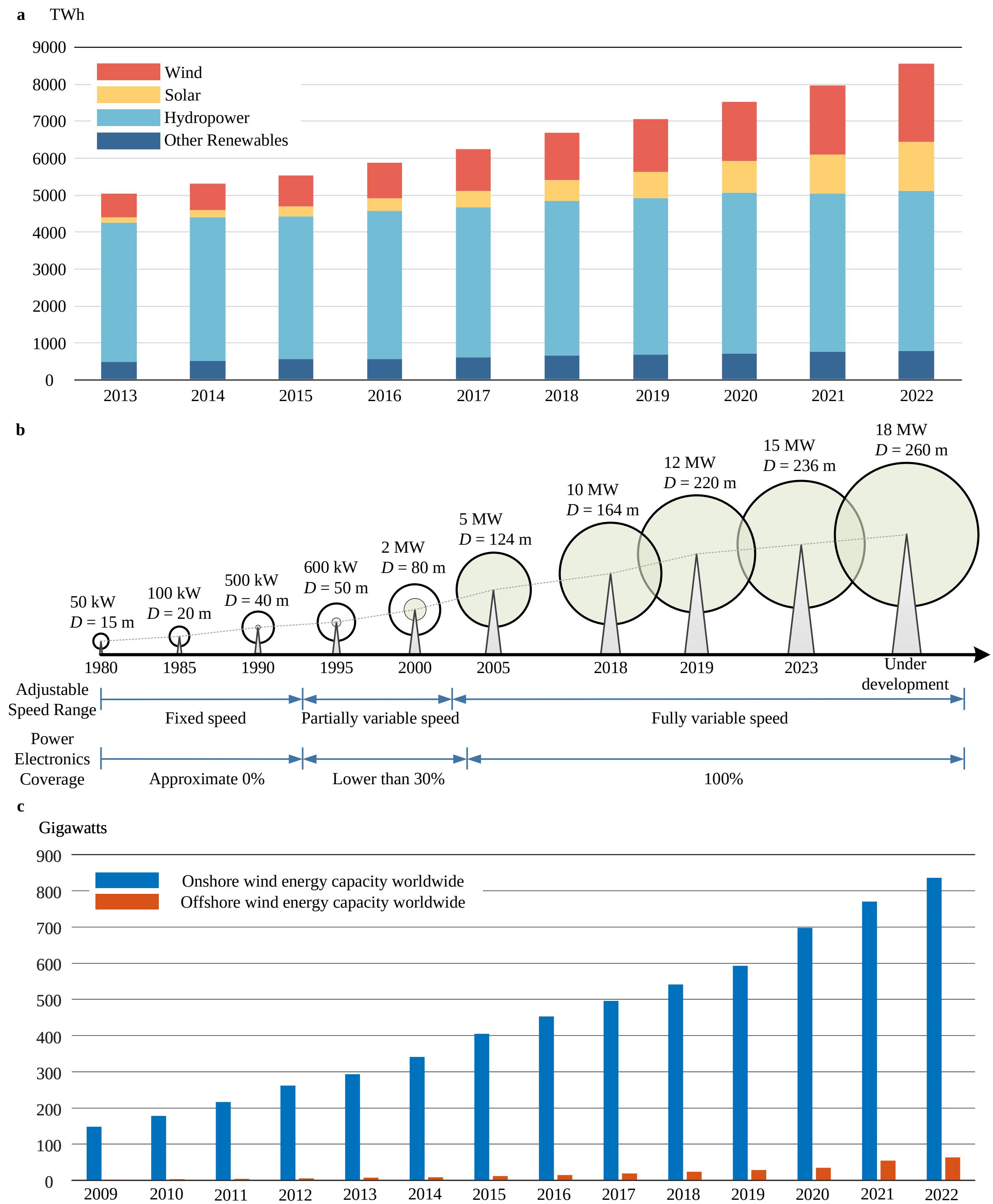

Figure 1. Development of wind generation systems. a, Comparison of renewable electricity generation worldwide. b, Wind turbine technologies. D: Diameter of the wind turbine rotor. "Green area": The power electronic coverage in total power. c, Wind energy capacity worldwide.

3. Reliability: Wind turbines are exposed to harsh environmental conditions, leading to wear and tear over time. Ensuring the long-term reliability and durability of turbines is essential to reduce maintenance costs and downtime. It is reported that even after turbines are certified, the new designs could run into unforeseen failures in the ocean. To enhance reliability, the use of predictive maintenance techniques, such as condition monitoring and data analytics, to detect early signs of mechanical issues or component failures, is a possible solution[46,47].

4. Engineering effort of high-power wind turbines: Although a larger size of the wind turbines can capture more wind energy, it poses potential engineering and logistical challenges. For example, large wind turbine components, such as the tower, blades, and nacelle, can be massive and heavy. Transporting them requires specialized equipment and vehicles capable of handling these loads. Besides, large ships are necessary to transport the wind turbines to offshore wind farms.

In addition, as the penetration of wind generation increases, wind generation systems become more and more critical in the modern electricity grid. So, it is required that a wind generation system should have the ability to withstand and recover from extreme disruptions or adverse weather conditions (e.g., high wind, storms, and lightning) while maintaining its capacity to produce electricity[48,49].

Grid Codes for Grid Integration

Grid codes are a set of technical requirements and guidelines established by grid operators and regulatory authorities to ensure a safe, stable, and efficient integration of renewable energy sources[50]. These codes vary from one region or country to another but generally focus on standardizing the connection and operation of renewable energy systems to maintain grid stability and reliability[51]. For the grid integration of WT generators, several common aspects are typically addressed in grid codes:

Active power regulation and frequency response: In a power system, the electricity supply and the demand should always be balanced to keep stable operation. Hence, wind generators are required to contribute to grid stability through active power and frequency control to help maintain the power balance in power systems[52].

Voltage and reactive power regulation: Grid codes specify the allowable range of voltage and frequency variations that wind generators must adhere to during grid connection. Wind generators are required to contribute to grid voltage stability by providing reactive power support and maintaining voltage within acceptable limits[53].

Fault ride-through (FRT) capability: Wind generators are expected to remain connected and operational during short-term grid disturbances, such as short-circuit faults. Grid codes define the minimum FRT capability, which ensures that WT generators can ride through faults and continue to supply power to support grid stability[54].

Power quality: Wind generators must meet specific standards for power quality, including limits on harmonics, flicker, and other electrical disturbances, to avoid adverse effects on other connected electrical equipment[55].

Grid connection and protection: Grid codes outline technical specifications for the connection of wind generators to the grid, including protection measures to isolate faulty equipment and prevent damage to the grid during abnormal operating conditions[55].

Communication and monitoring: Grid codes often require wind generators to be equipped with communication systems for remote monitoring, control, and data exchange with grid operators[56].

Power Electronics for Wind Generation Systems

As aforementioned, the grid integration of modern WTs dominantly relies on power electronic converters. So, power electronic technology has become the key technology for wind generation systems. In terms of power electronic technology, there are two vital areas: circuit topologies and control strategies. In this section, several commonly-used topologies will be reviewed and discussed. And various control strategies will be introduced in the next section.

General Configurations of Converter-based Wind Generation Systems

At first, two typical configurations of power electronic converter-based WT generation systems are presented, which are type-3 wind generation systems with DFIGs (Fig. 2a) and type-4 wind generation systems with permanent magnet synchronous generators (PMSGs) (Fig. 2b). Both of them have been widely adopted in modern wind power applications.

DFIGs are based on the induction generator principle. They consist of a wound rotor and a stator. The stator is connected to the grid directly, while the rotor is connected to the grid through power electronic converters (Fig. 2a)[57,58]. Since the power on the rotor side depends on the slip of the generator, only partial power goes through the power electronic converters, which allows a smaller power rating of the converter (e.g., 1/3 of the rated power). This partial conversion system reduces the size and cost of the power converters compared to full power converter wind turbines[59–64]. Besides, the power converters on the rotor side enable the generator to control the active and reactive power independently[65–68]. Moreover, they can also help the turbine to ride through these disturbances to keep stability. Despite these advantages, DFIG wind turbines have some limitations.

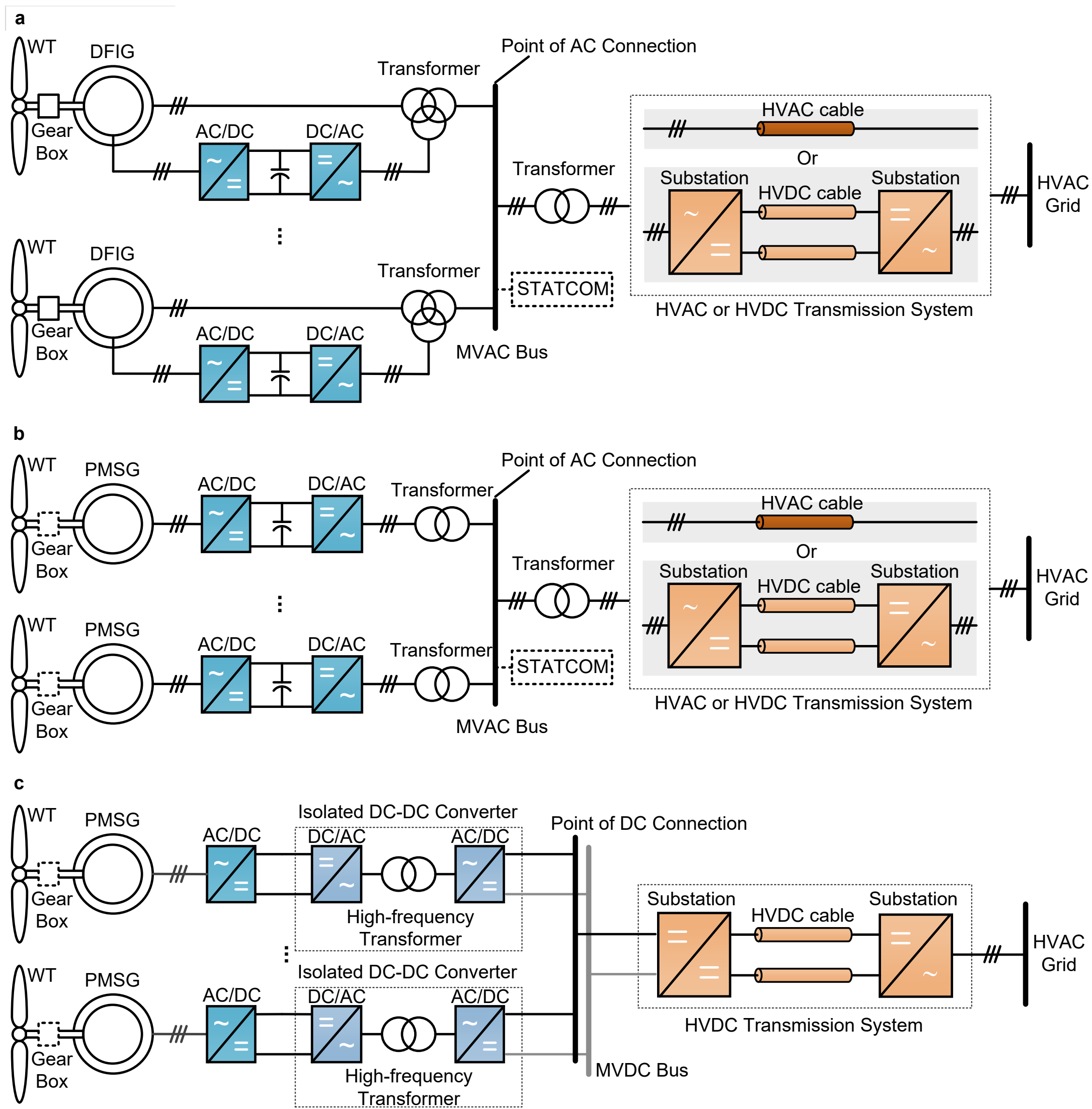

Figure 2. Configurations of converter-based wind generation systems. a, Type-3 wind generation system. b, Type-4 wind generation system. c, DC-connected wind generation system. WT: Wind turbine. DFIG: Doubly-fed induction generators. PMSG: Permanent magnet synchronous generator. STATCOM: Static synchronous compensator.

The power converters located on the rotor side requires slip rings or other rotating electrical contacts, which can increase maintenance needs compared to full power converter turbines[69].

Full power converter wind turbine is another type of wind turbine technology that utilizes power electronic converters to efficiently convert the power from wind turbine generator to the power grid. Full power converter wind turbines employ power electronic converters to convert the variable frequency and voltage output of the generator into a stable AC output that matches the grid frequency (Fig. 2b)[70]. This enables seamless integration with the electricity grid and facilitates the control of power flow[25,71]. Full power converter wind turbines remain advantages of the DFIG wind turbine, such as variable-speed operation, grid-friendly operation, and low voltage ride through (LVRT) capability[72–76]. Besides, different from the DFIG wind turbine, the full power converter wind turbine does not require slip rings. When the PMSG is equipped on the full power converter wind turbine, the gear box may be eliminated by using the direct drive design. Hence, the full power wind turbines might be more suitable for offshore wind applications. Overall, full power converter wind turbine generators have become increasingly popular in modern wind power project due to their high efficiency, grid-friendly operation, and high reliability[77,78].

Currently, the static synchronous compensator (STATCOM) is still broadly installed at wind farms, which can support the reactive power and voltage at the AC bus (Fig. 2a and b)[79]. Alternately, for some advanced WTs, they are able to provide

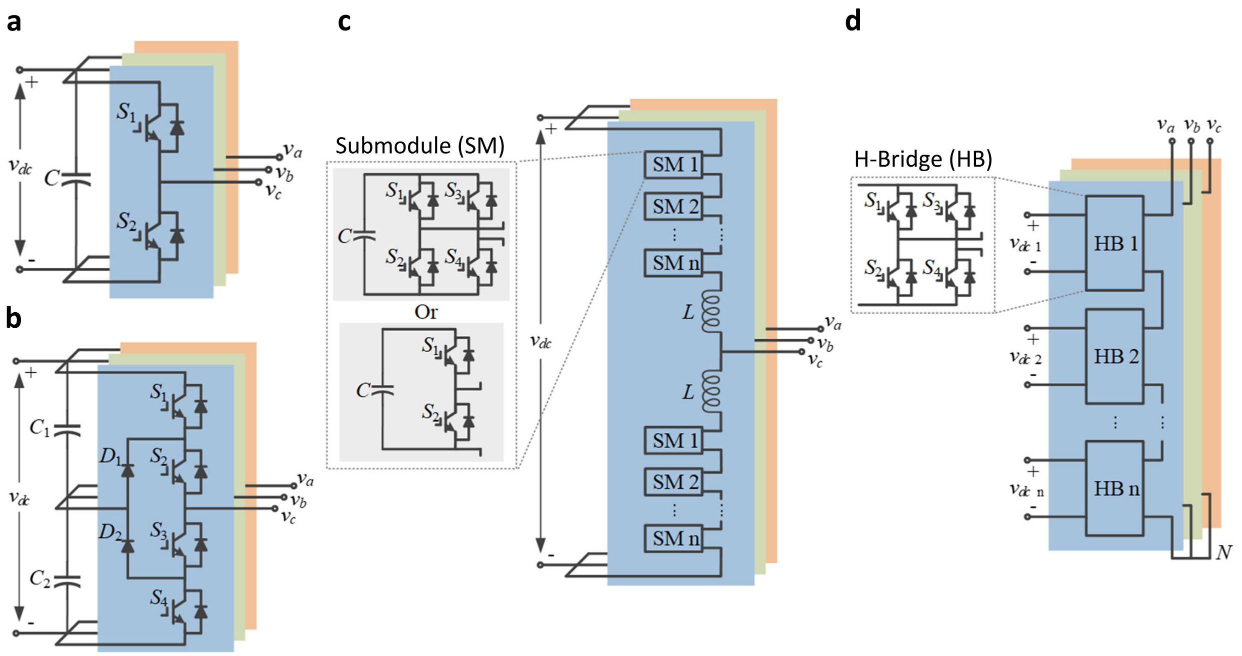

Figure 3. Topologies of grid-interfaced converters in wind power applications. a, Two-level converter. b, Three-level converter. c, Modular multi-level converter. d, Cascaded H-bridge multi-level converter.

reactive power support. Thus, the STATCOM may not be necessary in future wind farms. Moreover, collecting and delivering power at a wind farm scale involves a variety of technologies. Firstly, to collect the power from each wind turbine, there are centralized control strategies and distributed control strategies. For the centralized control strategies, the central controller sends voltage, power commands, and synchronization signals to each wind turbine. Then, the wind turbines follow the commands to adjust their operating status. Differently, for the distributed control strategies, each wind turbine has their own controllers. They can adjust their operating status based on local measurement and feedback control, without relying on the central controller. Secondly, the substation is a key component of a wind farm. It receives the electricity from the turbines, steps up the voltage for efficient transmission, and sends it to the grid through high-voltage AC (HVAC) cables. Alternately, the substation could be an MMC converter, changing the voltage form from AC to DC, then transferring the power to the grid through high-voltage DC (HVDC) cables (Fig. 2). In addition, energy storage systems, such as batteries, are increasingly being used in wind farms to store excess energy during periods of high wind and release it during low-wind periods or when grid demand is high. They can help to smooth the output power and also enable black-start functionalities. As the demand for clean energy sources continues to grow, wind farm technologies are evolving to meet these challenges and deliver a reliable and sustainable source of electricity.

Furthermore, there is another concept of DC-connected wind farm[80] (Fig. 2c). An isolated DC-DC converter is installed inside the wind turbine generator, which is used to increase the DC voltage from low voltage level to medium voltage level[81]. Notably, the high-frequency transformer could be either a single-phase transformer or a three-phase transformer. Then, all the wind turbine generators are connected on the MVDC bus. A major advantage of this scheme is that the volume and weight of the AC transformer can be reduced a lot by using a high nominal frequency (e.g., 1000 Hz) rather than the fundamental frequency (e.g., 50 Hz). Besides, the power conversion efficiency of this scheme is possibly designed to be higher than that of the AC-connected wind farm with bulk 50 Hz transformers. Meanwhile, the cost of the transformer is able to be reduced. However, to the best knowledge of the authors, this scheme has not been widely applied in practice. More research and engineering efforts are necessary to make this scheme applied in practice.

Typical Topologies of Grid-Interfaced Converters in Wind Power Applications

Afterwards, the specific topologies of the grid-interfaced converters will be discussed as follows. Three typical topologies of grid-interfaced converters in wind power applications are taken into account, which include a two-level converter, a three-level converter and a modular multilevel converter (MMC), respectively (Fig. 3).

The two-level inverter is the simplest type of inverter and consists of two voltage levels for each phase. It has been widely used in low voltage applications where the voltage is below 1000 VAC (e.g., 690 VAC)[82]. Besides, for a two-level inverter, an L-C filter has to be added to reduce the switching harmonics in the output voltage[83]. However, when the voltage level is higher than 1000 V, the application of the two-level inverter is rare due to the limited voltage rating of the power electronic switch.

The three-level inverter can address some limitations of the two-level inverter by providing an additional voltage level (0 V) between the positive and negative DC buses[84]. A major advantage is that a higher voltage (e.g., higher than 1500 VAC) can be generated by using the three-level inverter topology. Moreover, since the output voltage has three voltage levels, the harmonic distortion is lower than that of the two-level inverter. Hence, a smaller L-C filter is acceptable for the three-level inverter. However, the control complexity of the three-level inverter is higher than that of the two-level inverter due to the usage of more switching devices.

Furthermore, modular multilevel converters (MMCs) are able to go beyond three voltage levels, which can overcome the voltage limitations of two-level and three-level converters and further increase the output to tens of kilovoltages or even higher[85]. Hence, the MMC has become a promising solution for high-power high-voltage applications (e.g., tens of megawatt WTs)[86–88]. In addition, another advantage of the MMC is that the high voltage resolution can reduce the harmonic distortion and minimize the electromagnetic interference[89]. Overall, MMC technology is becoming increasingly important in modern power systems, particularly in offshore wind power plants. Its versatility and scalability make it more competitive in high-power and high-voltage applications. Moreover, cascaded H-bridge (CHB) is a popular choice for STATCOM due to its modularity, high voltage capabilities, low harmonics, and rapid response time (Fig. 3d). These characteristics make it an attractive choice for voltage regulation and power quality improvement in electrical systems, particularly in application where precise control and flexibility are required.

Operation and Control of Wind Generation Systems

Wind power systems play a key role in transforming wind energy into mechanical and electrical power in turn, facilitated by the WT and generator, respectively[80]. The mechanical power generated correlates with rotor speed, with its optimal value dictated by an MPPT algorithm to maximize energy capture[90]. It's imperative to curtail this mechanical power under excessive wind speeds, a task typically managed through blade pitch angle control[91]. The power conversion system, comprising machine-side converter (MSC) control and grid-side converter (GSC) control, facilitates the injection of electrical power into the grid in a grid-friendly way according to the grid code. The PMSG employs the stator-side converter (SSC) as the MSC[92], whereas the DFIG employs the RSC as the MSC[93]. A diverse range of control strategies have emerged to address the dynamics of wind generation systems. Within this review, our emphasis rests on the power electronics control, i.e., MSC control and GSC control, of the two widely used wind generation systems based on PMSG (Fig. 4a) and DFIG (Fig. 4b). Notably, among the following mentioned control methods, the types of proportional-plus-integral-plus-derivative (PID) control (including P, PI, etc.) are still the most applied methods for various loops in wind industry at present due to their good compromise between the simplicity and robustness. Other advanced control methods are still validated in the lab scale (such as model predictive control (MPC), sliding-mode control (SMC), etc.) or even almost in the simulation (such as intelligent control) due to their cost, complexities, and higher requirements on both hardware and software. Nonetheless, these restrictions may be broken as the development of technology. Therefore, advanced control methods, potentially providing better performance, can still be open topics for future.

Permanent Magnet Synchronous Generator

Machine-side (Stator-side) converter control

The control system of the PMSG typically follows a cascaded structure[94]. The outer loop may focus on rotor speed control to accurately follow a reference speed. This reference speed is often determined using an MPPT algorithm. Alternately, the outer loop may calculate the torque or active power reference according to the measured rotor speed and optimal tip-speed ratio. Then the inner loop controls the torque or active power accordingly, in addition to the voltage or reactive power.

The outer loop has been regulated by PI control, SMC[95], etc. The inner loop employs vector control within a rotating dq reference frame. In this frame, the q-axis control manages torque or active power, while the d-axis control handles voltage or reactive power[96]. Various control strategies, including PI control[97], fuzzy logic control (FLC)[98], and MPC[99], have been employed to design the dq control loops.

For quicker responses to changing wind speeds, a feedback-feedforward controller has been utilized for torque control[100]. Despite its simplicity, the cascaded structure achieves control indirectly by regulating dq currents. An alternative approach, known as direct torque/power control, eliminates the need for reference frame transformations and minimizes reliance on machine parameters, resulting in faster torque responses. This method has involved space-vector modulation and incorporated strategies like quasi-sliding-mode observers[101] or programmable low-pass filters[102] to reduce torque fluctuations while maintaining robustness even at low sampling frequencies.

To address disturbances and nonlinear modeling with low computational burden, SMC has been implemented. This method introduces different sliding surfaces such as PI-type surfaces[103], full-order surfaces[104], and provides good robustness against external disturbances. FLC also displays strong robustness against such disturbances[105].

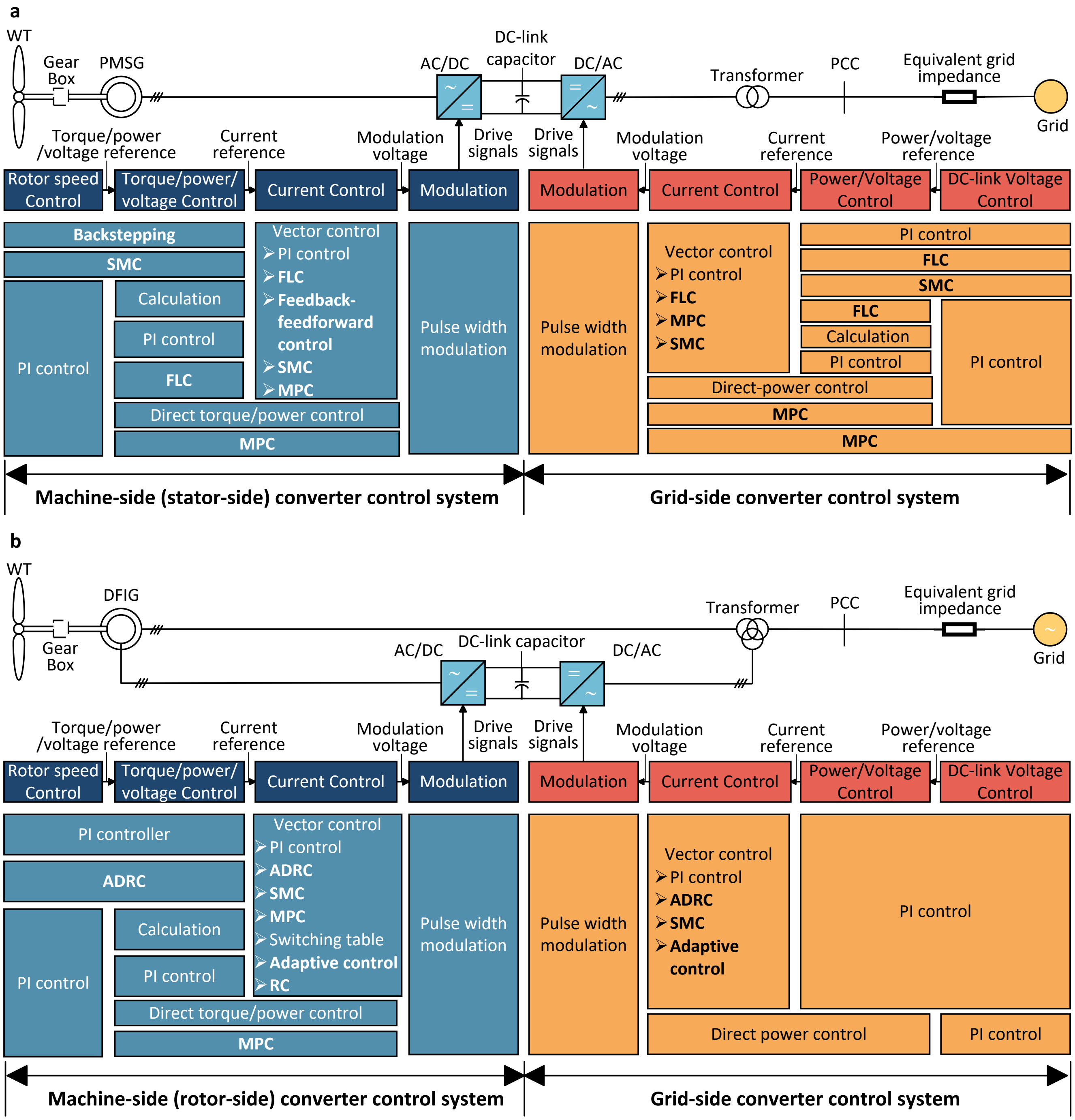

Figure 4. Summary of control strategies of wind generation systems. a, Permanent magnet synchronous generator (PMSG). b, Doubly-fed induction generator (DFIG). WT: Wind turbine. PI: Proportional-plus-integral. SMC: Sliding-mode control. FLC: Fuzzy-logic control. MPC: Model predictive control. ADRC: Active disturbance rejection control. RC: Repetitive control. PCC: Point of common coupling. Methods having not been widely used in industry and needing further research are marked in bold.

Another category of control strategies for SSC systems of PMSG is direct MPC, known for its rapid dynamics and capacity to handle multiple nonlinear constraints[106]. Enhanced variations of this approach have been explored to offer specific benefits. For example, by reducing the number of potential voltage vectors, the computational burden of direct MPC can be alleviated[107]. For stability requirements, the integration of the integrator back-stepping method with MPC can ensure Lyapunov stability condition[108].

These control strategies can involve fixed parameters or online optimization techniques such as the grey wolf optimizer algorithm[97], salp swarm algorithm[98], and chaotic-billiards optimizer algorithm[109]. Additionally, machine-learning methods like deep neural networks have been integrated to enhance control performance[99], taking advantage of their efficient online approximation capabilities.

Grid-side converter control

The conversion of DC power to AC power of the PMSG for feeding into the power grid is managed through GSC control, incorporating appropriate DC voltage regulation to maintain active power balance. Simultaneously, GSC control is tasked with regulating the reactive power injected into the power grid or the voltage at the point of common coupling (PCC). A widely adopted control strategy employs a cascaded structure like the SSC control, wherein the outer loop handles DC voltage control and reactive power/PCC voltage control, while the inner loop manage current control[96].

Various controllers, including PI controllers[97], FLC[98], and SMC[95] have been developed for all these loops. The current control loops are typically executed within the rotating dq reference frame. Due to the similar structure with the SSC control, the same online optimization methods of the grey wolf optimizer algorithm[97], salp swarm algorithm[98], and chaotic-billiards optimizer algorithm[109] have been applied to tuning the controllers of GSC control in addition to the strategy of fixed parameters. Another noteworthy approach for inner current control is the utilization of MPC, which is effective at accommodating nonlinear constraints of the grid-side when carrying out the optimization of the cost function[108].

Alternatively, current control can be executed in the stationary reference control and advanced techniques such as the terminal SMC have been applied for improved robustness[110]. Incorporating both PI-based DC voltage control and direct MPC have also been employed in the GSC control system of the PMSG to achieve rapid dynamics[106]. Enhancements in the robustness of direct MPC concerning system parameters have been realize through optimized switching tables[107]. The direct MPC can also encompass DC-link voltage control, which has demonstrated reduced tracking errors[106]. Additionally, considering DC-link voltage control cost function separately can eliminates the need for weighting factors, simplifying parameter tuning[111].

Doubly-Fed Induction Generator

Rotor-side converter control

The control system of the RSC of the DFIG typically follows a cascaded structure as well[112]. Various controllers such as PI controller[113], active disturbance rejection controller (ADRC)[114], etc., have been applied to the outer rotor speed control to track the reference speed from the MPPT algorithm. In the inner loop, vector control is implemented within a rotating dq reference frame. Here, the d-axis control manages torque or active power control, while the q-axis control handles PCC voltage or reactive power control. Different strategies, such as PI control[115], ACRC[114], and adaptive SMC[116], have been employed for constructing the dq loops. In comparison with PI controllers, ADRC and SMC demonstrate increased robustness to parameter uncertainties and disturbances. Additionally, model-free predictive current control has been established as an effective and robust techniques, as it does not require explicit system parameter use for current prediction[117].

Direct power control has emerged as an alternative to vector control, eliminating the need for inner current control. Inverter voltage vectors can be directly determined via power control using a PI controller[118] or switching table[119]. This approach, however, comes at the cost of steady-state performance due to larger ripple. A cascaded structure involving outer PI-based power control and inner switching table-based current control has been applied to RSC control. This strategy combines the advantages of low-ripple vector control and quick dynamics from direct power control[119]. Three-vectors-based direct power control has also been employed to reduce ripples by utilizing the zero vector[120]. In the stationary reference frame, voltage-modulated direct power control stands as a simple yet effective technique known for rapid and reliable power regulation[121].

Numerous nonlinear control methods are also available for the RSC control of DFIG, with MPC and adaptive control being most notable. MPC readily incorporates the nonlinear dynamics of DFIG. To streamline computation, input-output feedback linearization has been combined with continuous control set MPC[122]. Controller performance is often sensitive to model uncertainties and disturbances; thus, a disturbance observer has been introduced to mitigate these concerns[123]. In comparison with continuous control set MPC, finite control set MPC is more suitable for the RSC control, offering direct converter switching state outputs[124]. The application of adaptive backstepping-based control has enhanced the current control of the RSC, offering robustness against uncertainties without the need for additional observers[125]. For further performance improvements, adaptive MPC has been developed, combined the strengths of MPC and adaptive control[126]. Moreover, the MPC has also been combined with repetitive control (RC) in dq[127] and stationary reference frames[128], which leads to improved DFIG performance under distorted voltage conditions .

Grid-side converter control

The conversion of DC power to AC power for integration into the power grids is achieved through GSC control, which incorporate appropriate DC voltage control to maintain active power balance in the system[123]. Concurrently, the GSC control is

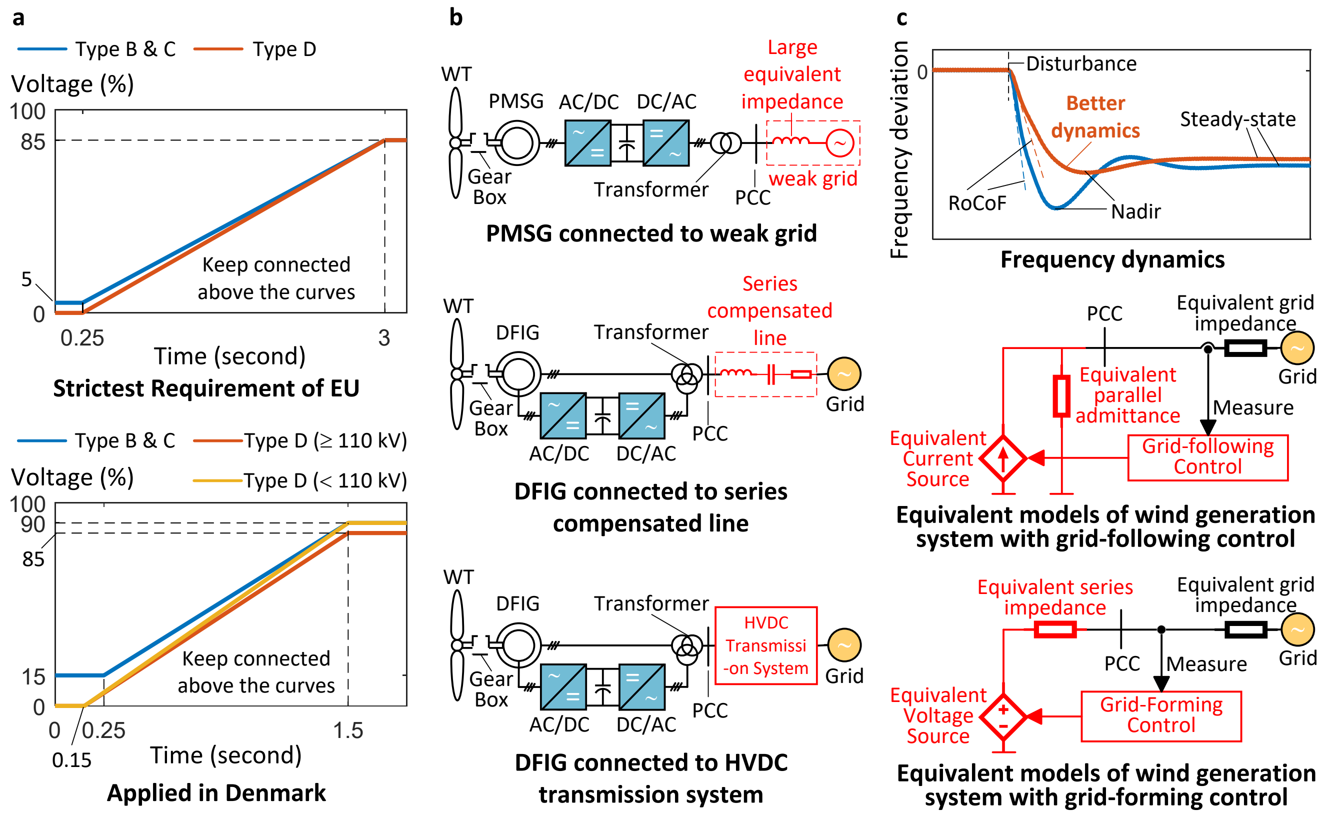

Figure 5. Issues when wind generation systems are integrated into the power systems. a, Strictest requirement of low-voltge ride through defined by EU and adopted in Denmark[129,130]. b, Three types of integration that may lead to subsynchronous oscillations[131–133]. c, Frequency support function. Grid-forming control with voltage source characteristics generally has better frequency support ability than grid-following control with current source characteristics[13]. WT: Wind turbine. PMSG: Permanent magnet synchronous generator. DFIG: Doubly-fed induction generator. PCC: Point of common coupling. RoCoF: Rate of change of frequency.

also responsible for the regulation of reactive power injected into the power grid. Like in all sections above, a widely adopted control strategy employs a cascaded structure, wherein the outer loops manage DC-link voltage control and reactive power control, while the inner loops govern current control[112]. As the power conversion system of DFIG only endure partial-scale power, the GSC control of DFIG is hardly drawn attention as much as the RSC control. Typical methods of the RSC control can be applied to the GSC control as well. PI controllers are commonly used for all those loops of the GSC control, with current control loops implemented within the rotating dq reference frame[115]. Enhanced control approached used in RSC control, like adaptive SMC[116] and the ADRC[114], have also been implemented to the GSC control, due to their features in improving robustness against disturbances. For the purpose of eliminating the need for current loop utilization and yielding faster dynamic responses, the direct power control has been applied to the GSC as well[118]. Other alternative approaches for the GSC control are voltage-modulated direct power control[121], adaptive backstepping-based nonlinear control[125], etc.

Application of Wind Generation Systems in Power Systems

As wind generation systems increasingly replace synchronous generators in power systems with significant penetration, higher requirements exerts to them. These requirements come from two aspects. Firstly, the wind generation systems must well operate under diverse grid conditions and disturbance arising from interactions between wind generation systems and the grid. Secondly, wind generation systems are mandated to provide various auxiliary services to ensure the optimal operation of the power systems. Within this scope, key areas of concern include LVRT capability, subsynchronous oscillation damping, and frequency support, which are of great importance and are further explored within this review.

Low-Voltage Ride Through Capability

Wind generation systems can be categorized into Type A, B, C, and D by their capacities and integrated voltage levels in the EU and Denmark. Specifically, Type A means connection point below 110 kV and maximum capacity of 0.8 kW or more, Type B connection point below 110 kV and maximum capacity of 125 kW or below, Type C connection point below 110 kV and maximum capacity of 3 MW or below, and Type D connection point at 110 kV or above[129]. In accordance with grid codes, wind generation systems of Type B, C, and D are mandated to maintain connection and inject reactive current during grid faults characterized by voltage sags, known as LVRT capability. In EU, general requirements have been defined and, as the basis, different member states have the requirements of their own (Fig. 5a)[129, 130]. Typically, LVRT involves introduction of an additional reactive current reference, which can be fixed[134] or proportional to voltage deviations during faults, often through methods such as table look-up[135] and proportional controller[136]. Nonetheless, it is imperative to ensure that voltage sags do not result in power converter damage and system instability, a prerequisite for secure LVRT[137]. This property can be achieved through hardware enhancements and advanced control strategies.

In the hardware-focused approach, most of the DFIG-WTs are involved in crow-bar protection as the conventional LVRT method, which has also been studied and applied in the PMSG-WTs[138]. This approach ensures system safety during faults by diverting wind power through the crow-bar resistance, thereby keeping the system variables within their limits[139]. Altering the transformer structure within wind power systems offers the ability to regulate stator voltage to nominal levels, irrespective of potential grid voltage changes[140].

In the control-focused approach, various strategies have been developed to enhance LVRT capability by modifying control structures, primarily aimed at limiting power to the DC-link bus for improved performance. A straightforward method involves constraining modulating signals[139]. Alternatively, adjusting power references, such as replacing the MPPT control with DC-link voltage control during LVRT, allows wind power to be stored as kinetic energy without feeding into the DC bus[141], or dynamically altering power references based on the degree of voltage sag[142]. It has been noted that the integrator within the DC-link voltage PI controller may restrict transient response speed and destabilize the system during LVRT. Therefore, disabling the integrator has been proposed to enhance LVRT capability[143]. Additionally, proper control of the RSC facilitates the decay of the stator DC component, effectively constraining rotor voltage and current[144]. The stability of wind generation systems during LVRT is also influenced by the phase-locked loop (PLL), where decreasing the PLL bandwidth can improve LVRT capability[145]. Asymmetric LVRT capability is also crucial, often addressed by providing appropriate positive-sequence and negative-sequence reactive currents. The asymmetric LVRT capability has been enhanced through a negative-sequence PLL with increased damping and improved dynamics[146].

Subsynchronous Oscillation Damping

Subsynchronous oscillation, characterized by ongoing energy exchange at frequencies below the fundamental frequency, poses a significant hazard to the secure and stable operation of both WTs and the power grid[147]. Diverse mechanisms have been identified as contributors to subsynchronous oscillation excitation (Fig. 5b). In instances where PMSGs are connected to weak grids, a negative resistance effect can induce unstable oscillations, resulting in subsynchronous oscillation occurrence. This adverse effect can be mitigated by introducing supplementary damping signals within the d-axis current control of the GSC[131].

Similarly, in the case of DFIGs, subsynchronous oscillation may be triggered when connected to series-compensated systems[132]. Various strategies have been implemented to dampen this subsynchronous oscillation. The excitation of the synchronous oscillation is significantly linked to the characteristics of the current controller. Proper tuned PI parameters can offer subsynchronous oscillation suppression to some extent[148]. On another front, advanced controllers like $\mathscr{H}_\infty$ controller[149], feedback linearization controller[150], and sliding-mode controller[151] have been deployed to replace conventional PI-based current controllers, effectively mitigating the subsynchronous oscillation. Furthermore, supplementary subsynchronous damping controllers have been introduced to aid in dampening the subsynchronous mode[132]. These supplementary controllers use appropriate filters to extract subsynchronous components, where the damping function can be implemented via either inner software system[152] or an external shunt voltage-source converter[153]. To cope with the time-varying characteristics, the model-free control strategies have been used to improve the robustness of the subsynchronous damping controllers[154]. Notably, subsynchronous oscillation occurrences are also witnessed when DFIGs are interconnected with HVDC grids due to their interaction[133]. This kind of subsynchronous oscillation has been dampened by introducing additional filters to reshape the impedance characteristics[155].

Frequency Support

The grid frequency support ability of the wind generation systems is highly related to the synchronization mechanism. The conventional synchronization of wind generation systems with the power grid using PLLs typically involves power injection without offering frequency support. However, this approach may lead to deteriorated frequency response in the power system, characterized by lower frequency nadir, higher rate of change of frequency (RoCoF), and reduced steady-state value, particularly as the penetration level increases (Fig. 5c). This control strategy is referred to as grid-following (GFL) control, which is equivalent to a current source operation that needs external voltage source support to maintain the frequency stability (Fig. 5c). Numerous strategies grounded in GFL control have been proposed to offer frequency support without the need of additional devices.

The first approach involves operating the wind generation system with power reserve, achieved by shifting the MPPT reference. Alternatively, the kinetic energy of the wind turbine generator can be released by adjusting rotor speeds during frequency events.

In the first method, the pitch angle can be regulated based on the frequency deviations, enabling power reserves to participate in primary frequency control[156]. Otherwise, the wind generation systems can operate with various deloading schemes[157]. In the second approach, the active power reference is altered from the MPPT power during a frequency event. The deviated power is then used to stabilize frequency variations, followed by an adjustment of the active power reference in the opposite direction to restore rotor speeds. Various forms of active power reference adjustments exist, such as step variations, gradual variations[158], rotor speed-based variations[159], delay-based logic[160], Gaussian distribution variations[161], or machine-learning-tuned variations[162]. The power reference can be set explicitly emulating the behavior of conventional synchronous generators as well. For instance, deviated power can be determined based on the frequency derivative to replicate inertia characteristics[163]. Unlike actual synchronous generators, the inertia constant in the control system is virtual and not constrained by physical limitations. Building upon this notion, the use of a time-varying inertia constant has been demonstrated to yield superior performance compared to a fixed value[164]. Similarly, frequency deviation can also be employed to modify the power reference, emulating primary control in conventional synchronous generators[165].

In recent times, a novel control strategy known as grid-forming (GFM) control has emerged, exhibiting good frequency support capabilities (Fig. 5c). GFM control entails power synchronization and make the wind power systems to be equivalent to voltage sources, which can actively build the frequency reference by itself like a synchronous generator. The same as the GFL control, energy buffers can be derived from energy curtailment and kinetic energy of the wind generator rotor. The energy buffers, when combined with diverse GFM control strategies such as droop control[166], virtual synchronous generator control[167], virtual oscillator control[168], and matching control[169], facilitates inertia provision and rapid primary frequency control.

Selected EU Projects of Wind Generation System

The harnessing of wind energy stands as a critical and prominent research topic within the energy landscape of EU, especially in Denmark, which is known as one of the leading countries in wind energy worldwide. In recent times, a list of projects have been awarded to explore various aspects of wind power energy for the purposes of either academic research or industrial requirements, benefited from diverse funding sources including Horizon Europe, Energy Technology Development and Demonstration Program (EUDP), Danish Energy Agency, and more (Table 1). Among the selected projects in this review, CONTINUE strives to develop WT side control, while DIGIT-BENCH focuses on the development of digital test benches for the wind industry. InterOPERA is specialized in the development of HVDC for wind integration. Meanwhile, the WinGrid initiative is dedicated to comprehensively studying the modeling, stability, and control aspects of power-electronics-based wind power systems. Other projects, i.e., Denmarks's Energy Islanded and OEH, are grounded in the context of integrating Denmark's isolated offshore wind farms.

CONTINUE. *Control of next-generation wind turbines (CONTINUE)* is a *development and demonstration, including research* project from 2023 to 2026 funded by EUDP. The objective of CONTINUE is to develop and demonstrate a novel "flow-field-aware wind-turbine controller", which enables the wind-turbine to react to the full turbulent field based on the measurements and estimations. To this end, the project will develop a hub lidar for precision wind velocity measurements and an estimator for real-time full-field turbulence estimation. A novel control algorithm using those measurements and estimations to give a dynamic feedback will be developed as well. This project involves the demonstration of a prototype of the developed wind turbine control system on an actual wind turbine with the rated power greater than 2 MW. The project aims to reduce tower loads, cost, and carbon emissions of the wind turbine, in addition to other benefits provided by wind data of measurements and estimations of the developed control system.

DIGIT-BENCH. *Digital twin for large-scale test benches for the wind industry (DIGIT-BENCH)* is a *development and demonstration* project from 2023 to 2025 funded by EUDP. The objective of DIGIT-BENCH is to develop and demonstrate large-scale test benches for wind industry using the digital twin technique. Due to the development of bigger and bigger wind turbines, their test cost is increasing for industry involving bigger test equipment and longer test time. DIGIT-BENCH aims to develop software framework so that the physical experiments can be replaced by virtual ones. The outcome of the project will be demonstrated on the world's largest highly accelerated lifetime testing (HALT) test bench at Lindø Offshore Renewables Centre in Denmark. The project will also establish technological development roadmaps for the purpose of future commercialization.

InterOPERA. *Enabling interoperability of multi-vendor HVDC grids (InterOPERA)* is funded under *Innovation action* scheme of EU's research and innovation funding programme Horizon Europe, which starts from 2023 and will last four years. InterOPERA unites twenty-one participants leading in wind energy including transmission system operators, industrial manufacturers, sector associations, and universities to fully investigate the HVDC-related topics for wind energy integration, especially offshore wind, covering technology, economy, policy, etc., among multi-stakeholder. The project aims to develop the modular techniques and standardized frameworks of HVDC to enable the multi-stakeholder cooperation. Such cooperation will highly improve the expansion of wind energy integration in the future. At the meantime, grid-forming ability of the wind generation systems to support the power system is highlighted in InterOPERA. The project is with a focus on the EU's target of deploying 300 GW of offshore wind by 2050, which is almost five times of the capacity worldwide in 2022 (Fig. 1c).

WinGrid. *Wind farm - grid interactions: exploration and development (WinGrid)* is funded from October 2019 to March 2024 under *Marie Skłodowska-Curie Action* of Horizon Europe. The project is carried out by participants around EU from both academia and industry, and focuses on the power system integration of wind generation systems, involving a wide research scope of modeling, interaction, control, and stability. Specifically, WinGrid will evaluate the dynamic interaction between turbines within a wind farm, multiple wind farms, as well as between wind farm and grid. Meanwhile, the project will fully explore the ability of wind generation system participating in power system auxiliary services focusing particularly on frequency support. Furthermore, grid-forming control based on a so-called synchronverter applied in the wind generation system is explored its potential in improve the dynamics of the power system. The project will also research the integration of wind generation system combining with other renewable such as energy storage and PV. WinGrid is a project of innovative training networks for next generation of researcher and future research is expected to be carried out.

Denmark's Energy Islands. Denmark is known for its abundant wind energy, where isolated offshore wind farms play an important role in supplying clean electricity to Danish grid. For a more efficiently integration, Danish Energy Agency is leading an ambitious plan to develop the world's first energy island. The energy islands will serve as energy hubs for collecting, converting, and distributing clean electricity from offshore wind farms between several neighbouring countries. Denmark's Energy Islands involves two energy islands in the Baltic Sea and North Sea, respectively. The energy island in the Baltic Sea will be based on the island of Bornholm to place the electrotechnical equipment and the offshore wind farms will be located 15 km south-southwest of the coast (Fig. 6). As for the energy island in the North Sea, an artificial energy island will be built for the purpose to place the electrotechnical equipment. It is expected to produce 3 GW from the energy island in the Baltic Sea and 3-4 GW electricity for the first phase and up to 10 GW electricity from the energy island in the North Sea. Such electricity can supply not only Denmark but also neighbouring countries, where agreements have been reached with Germany, Netherlands, and Belgium. It is worth noting that the project is also with specific focus on Power-to-X.

OEH. *Offshore Energy Hubs (OEH)* is a *development and demonstration, including research* project from 2022 to 2026 funded by EUDP. The project is expected to serve the Denmark's Energy Islands by providing technical solutions for critical aspects. Specifically, three themes and technical issues will be addressed. For the energy hub, tools and control strategies will be developed to achieve a stable and resilient operation. For the offshore wind farms, cost-efficient design method will be developed. It contributes to shift the grid code requirements from wind farms to energy hub. For the Power-to-X issue, hub-optimized offshore Power-to-X will be developed, which is expected to be more cost-efficient providing stable and flexible services to the energy hub. The project aims to not only improve economic benefits of the two energy islands of Denmark, but also provide feasibility for extendable offshore energy hubs in the future.

Outlook

The future development of wind power generation requires consideration of key areas by academia and industry, arranging from wind turbine, power systems application, to corresponding policies.

Since the development of onshore wind energy resources worldwide tends to be saturated, offshore wind energy resources are expected to be developed more in the future. Compared with traditional fixed-bottom wind turbines, floating wind turbines offer great potential for harnessing wind energy in deep waters, which can expand geographical locations for offshore wind energy production (Fig. 7a). Therefore, floating wind turbine technology has attracted lots of research attention[40]. However, due to the dynamic nature of the platform under the condition of varying waves and wind, the design of floating wind turbines might be complex. Besides, laying undersea cables over long distances between offshore wind farms and the onshore grid may be costly and may encounter operation challenges, which need further study.

In order to have better wind energy capture capability, the size and capacity of wind turbines are continuously increased year by year. According to this trend, the capacity of wind turbines is expected to be further increased in the future (Fig. 7b). However, high-power wind turbines require advanced power electronic technology such as three-level converters and MMC topologies to increase the voltage levels and power transmission capability. Then, power losses, stability, reliability, insulation, and protection issues of power electronic systems may face some new challenges in medium or high-voltage applications, which are important research directions.

The use of advanced controls except for conventional vector control can provide superior performance. In an actual power system, multiple wind generation systems will lead to interactions between each other[171]. In addition to evaluate the

Table 1. Summary Table of Selected Projects.

Project	Timeline	Participants	Funding	Website
Control of next-generation wind turbines (CONTINUE)	2023 -2026	Technical University of Denmark Vestas Wind Systems	EUDP	https://eudp.dk/en/node/16680
Digital twin for large-scale test benches for the wind industry (DIGIT-BENCH)	2023 -2025	R&D Test Systems A/S Aarhus University Lindø Offshore Renewables Center	EUDP	https://eudp.dk/en/node/16679
Enabling interoperability of multi-vendor HVDC grids (InterOPERA)	2023 -2027	SuperGrid Institute, 50hertz, Amprion Energinet, equinor, GE, Hitachi Energy, Østed, RTE, Scibreak, Siemens Energy, Siemens Gamesa Renewable Energy, Statnett, T&D Europe, TU Delft, TenneT, Terna Driving Energy, University of Groningen, Vattenfall, Vestas, WindEurope	Horizon Europe	https://interopera.eu/ https://cordis.europa.eu/project/id/101095874
Wind farm - grid interactions: exploration and development (WinGrid)	2019 -2024	University of Warwick Aalborg University Imperial College London Christian-Albrechts-Universität zu Kiel Technical University of Denmark University College Dublin Tel Aviv University DNV	Horizon Europe	https://www.wingrid.org https://cordis.europa.eu/project/id/861398
Denmark's Energy Islands	Long-term	Leading by Danish Energy Agency	DEA	https://ens.dk/en/our-responsibilities/energy-islands
Offshore energy hubs (OEH)	2022 -2026	Technical University of Denmeark Aalborg University Siemens Gamesa Renewable Energy Green Hydrogen Systems Ørsted Energy Cluster Denmark Energinet	EUDP	https://www.eudp.dk/en/node/16644

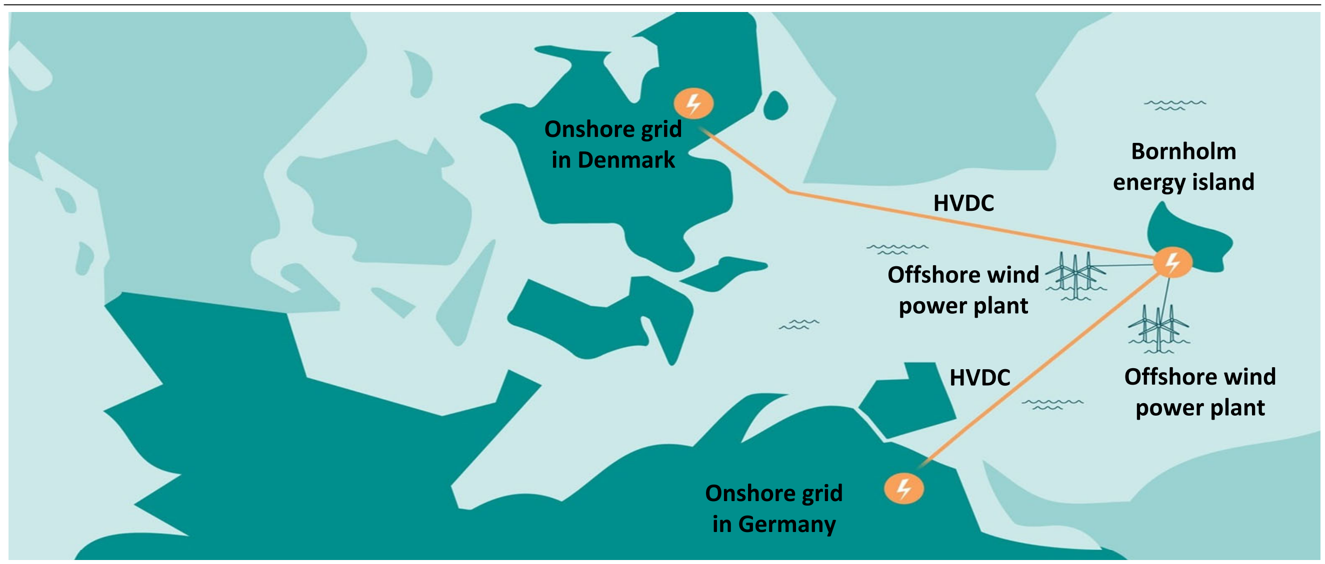

Figure 6. Bornholm Energy Island[170].

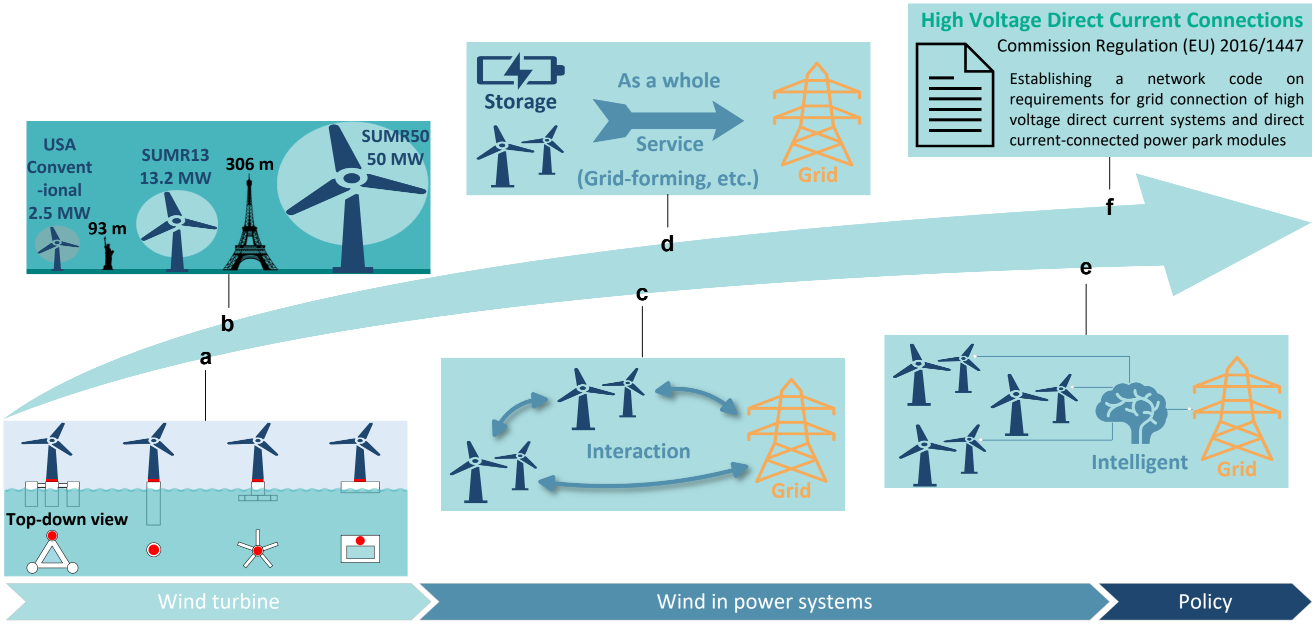

Figure 7. Future trends in wind power generation systems. a, Floating wind turbine. b, High-power medium/high-voltage wind generation systems. c, Interaction mechanism and control at system-level. d, Application of energy storage systems. e, Artificial intelligence-enabled wind generation systems. f, Policy improvements.

performance of a single machine system, those interactions should be explored further and any negative effects should be well addressed and mitigated. Furthermore, requirements on wind generation systems could be different leading to distinguished control strategies such as grid-forming control and grid-following control. Their interactions as well as considering the dynamics of the wind turbines, especially for the grid-forming control, should be fully investigated as well. In the scenario of high penetration of wind power systems, characteristics of the integrated grid may not be simply represented by an ideal grid with an impedance in series. This system-level analysis and validation is necessary before widely applying those advanced controls in practice (Fig. 7c).

Energy storage is critical for the future sustainable power systems as its power is dispatchable. The energy storage can be used to smooth the power output of the wind generation systems. More important, with the help of the energy storage, acting as energy buffer, it will be much easier for the wind generation systems to provide various auxiliary services[172], e.g., frequency regulation with GFM ability, black start, stability improvement, power dispatching, etc. Compared to the wind solutions, the use of energy storage can avoid critical issues such as secondary frequency drop and power deloading. Combined wind and energy storage system with multi-functions is promising to explore (Fig. 7d). It can be expected that progresses of energy storage and cooperative control with wind energy systems will highly promote the development of wind energy systems. As for GFM, at present, there is still no standard for guiding industrial applications although some efforts are going on. Meanwhile, as the GFM control relies on energy buffer, which may imply higher complexity and cost, it is still an open topic what is the optimal required ratio of the GFM control.

Interdisciplinary research will be required to optimize future development. Data science and artificial intelligence (AI) in the wind generation systems are drawing growing attention (Fig. 7e), which can be used in various aspects, ranging from wind speed prediction, parameter estimation for assisting control design, to system-level optimization[173,174]. Aside from the points mentioned above, reliability is another critical factor for the future development of wind turbines. Currently, the industrial lifetime of a wind turbine is 20 years. When some reliability-enhanced methods are applied to avoid stressful operation conditions, it is possible to increase the lifetime of a wind turbine[175]. For example, tailored physics-informed AI tools may address longstanding challenges in condition monitoring so as to improve the failure prediction and reliability. Although preliminary exploration has started, it is still far away from wide utilization in practice.

Beyond the technical issues, policies are remained to improve as well. The applications of offshore wind power plants are with special attractions in the future, where HVDC transmission lines are usually utilized to transfer the power from offshore substations to onshore grids. In this case, the offshore grid voltage is provided by the converter in the offshore substation. Typically, only wind farms are connected to the offshore grid without any loads. Thus, the grid code in such cases is possible to be not exactly the same as that of conventional power grids. In Europe, new grid codes for HVDC-connected grids have been released (Fig. 7f). However, the contents in the new grid codes are still too broad. Further specification of the new grid codes from a cost-effective perspective could be valuable work.

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Highlighted references

1. Ref. 13: This article highlights the role of power electronics in the integration of renewable energy.
2. Ref. 30: This article compares the advantages of horizontal axis wind turbine and vertical axis wind turbine.
3. Ref. 39: This article discusses future trends of floating offshore wind turbines.
4. Ref. 45: This article discusses the real-world subsynchronous oscillation events with integration of wind power.
5. Ref. 80: This article presents state-of-the-art technologies of high-power wind energy conversion systems.
6. Ref. 86: This article reviews operation, control and application of the modular multilevel converter.
7. Ref. 99: This article presents an case that the developing intelligent control can be integrated into the control of wind power systems.
8. Ref. 135: This article studies the potential small-signal instability issue of DFIG-based wind turbines during LVRT.
9. Ref. 166: This article investigates the PMSG participating in the frequency regulation in a promising grid-forming way.
10. Ref. 175: This article introduces the reliability of power electronic systems from an industry perspective.

Competing interests
The authors declare no competing interests.

Short summary
This article reviews current achievements and challenges of different power electronic technologies from a single wind turbine to a system level. Besides, several projects are reviewed to observe current research focus. Finally, future trends of wind power generation are summarized.