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Power Electronics: The Enabling Technology for Renewable Energy Integration

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***Abstract*—The markedly increased integration of renewable energy in the power grid is of significance in the transition to a sustainable energy future. The grid integration of renewables will be continuously enhanced in the future. According to the International Renewable Energy Agency (IRENA), renewable technology is the main pathway to reach zero carbon dioxide (CO2) emissions by 2060. Power electronics have played and will continue to play a significant role in this energy transition by providing efficient electrical energy conversion, distribution, transmission, and utilization. Consequently, the development of power electronics technologies, i.e., new semiconductor devices, flexible converters, and advanced control schemes, is promoted extensively across the globe. Among various renewables, wind energy and photovoltaic (PV) are the most widely used, and accordingly these are explored in this paper to demonstrate the role of power electronics. The development of renewable energies and the demands of power electronics are reviewed first. Then, the power conversion and control technologies as well as grid codes for wind and PV systems are discussed. Future trends in terms of power semiconductors, reliability, advanced control, grid-forming operation, and security issues for large-scale grid integration of renewables, and intelligent and full user engagement are presented at the end.**

***Index Terms*—Advanced control, grid codes, grid integration, photovoltaic system, power electronics, reliability, wind turbine system.**

I. INTRODUCTION

RAW material shortages and environmental pollution due to conventional energy sources (e.g., coal and oil) are the main obstacles to the global strategic sustainability plans. Following the Paris Agreement of 2015, there is a need to achieve energy transition by the development and utilization of renewable energy sources (RESs). Accordingly, many countries have made substantial efforts to change their energy paradigms by intensively integrating RESs, e.g., wind, solar photovoltaic (PV), bioenergy, and ocean wave energy, into their energy systems [1]–[3]. For instance, Denmark plans to be 100% independent of fossil fuels and 100% carbon-neutral based on RESs by 2050 [2]. IEA (2020) reported that driven by strong policy support, Germany has rapidly increased the share of renewable energy in its electricity generation in the recent past [3]. Seen from the global landscape of renewable energy, the RES capacity has grown remarkably in the past two decades, as shown in Fig. 1 [4]. In addition, the development of global RESs in the immediate past, i.e., from 2000 to 2020, is depicted in Fig. 2, where wind and solar PV sources have the highest growth rates [4].

There are mainly two challenges that accompany the high penetration of RESs. One is how to friendly integrate large-scale RESs into the electrical grid, ensuring network stability when injecting varying renewable power, as well as in case of grid disturbances. The other is how to achieve efficient, intelligent, and reliable power conversion, transmission, distribution, and utilization of electrical energy by using power electronics. Accordingly, power electronics technologies have been developed at a fast pace, and the grid-integration standards are continuously being updated for RESs, especially in the case of wind and PV systems [5]–[13].

Regarding power electronics technology, many advancements have been made along with the development of power semiconductor devices, as shown in Fig. 3 [14]. From the first-generation power semiconductor devices (i.e., thyristors) in 1957 to the third generation of fully controlled power switches, e.g., insulated gate bipolar transistor (IGBT) and metal-oxide-semiconductor field-effect transistor (MOSFET) in the 2000s [15], [16], research efforts have mainly focused on gate drivers, circuit topologies, modeling, and control strategies to achieve high switching frequencies (for high power density), low losses, and high power handling capability in power electronics-based power converters. As demonstrated in Fig. 3, the development of wide-bandgap (WBG) devices, e.g., silicon carbide (SiC) and gallium-nitride (GaN) power devices, brought the second revolution due to their superior performances in terms of high voltage/current stress, low power losses, high switching frequencies, and high-temperature operation capability [17], [18]. On the other hand, in practical applications, WBG devices are usually accompanied by new challenges, e.g., packaging, thermal management, and electromagnetic interference (EMI). Nevertheless, advancements in semiconductor technologies have enhanced the large-scale grid integration of RESs, however, lowering the system costs is still of concern.

In the past, power converter topologies for low power RESs mainly focused on high power density and high efficiency, and they had to satisfy the requirement of electrical isolation between the low voltage side and the grid [19]. Generally, such

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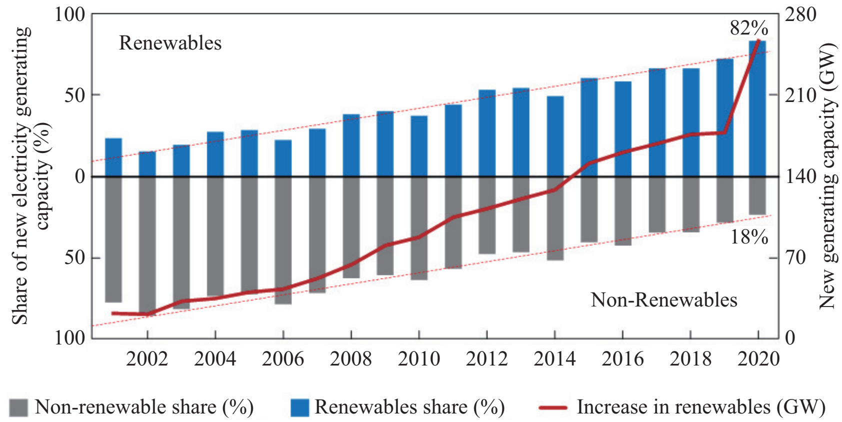

Fig. 1. Comparison of RESs and non-RESs as a share of the total global annual additions based on the data available from IRENA [4], where the net increase in global renewable generation reached 261 GW in 2020.

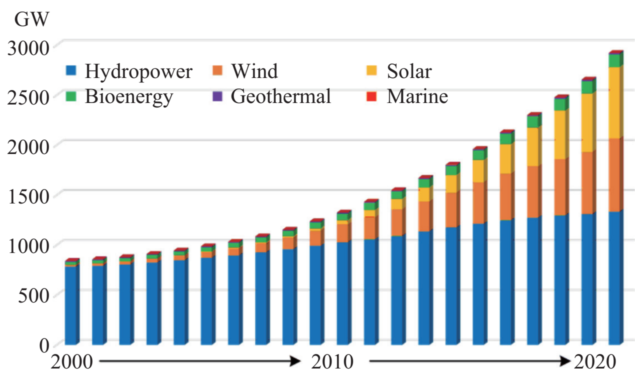

Fig. 2. Global accumulated capacity of RESs from 2000–2020 based on the data available from IRENA [4]. Here, hydropower covers pumped storage and mixed plants, wind contains both onshore and offshore wind energy, solar includes photovoltaics and solar thermal, and marine includes tide, wave, and ocean energy.

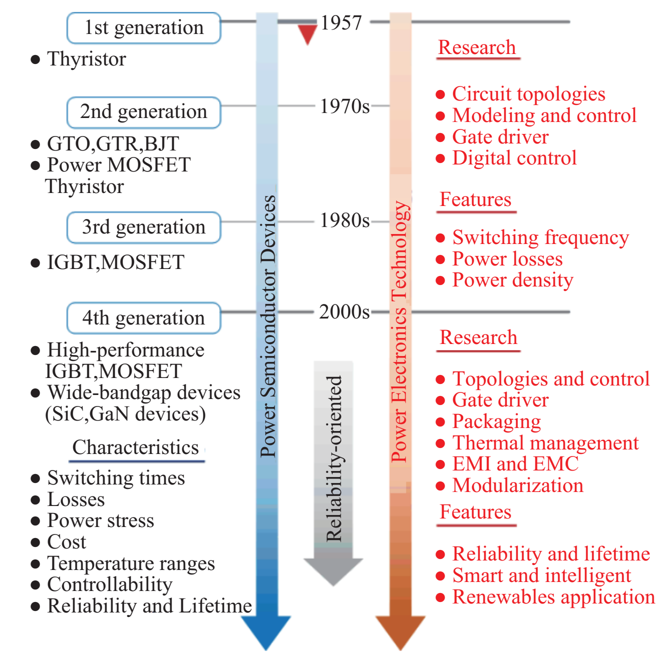

Fig. 3. Development of power electronics technology along with the evolution of RESs and power semiconductor devices (Adapted based on the discussions in [14]).

grid-connected converters can be classified into transformer-based and transformer-less topologies. By comparison, the transformer-less topologies are more efficient, more compact, smaller in size, and less costly than transformer-based converters. In addition, micro-inverters employed for low-power PV systems have the advantages of high voltage gain, plug-and-play, and the ability to maintain maximum power point tracking (MPPT) for each PV panel [20]. On the contrary, power converters for large-scale RESs, e.g., wind power plants, pay more attention to high power level, high voltage, and high reliability [21]. It has been seen in practical industrial applications that the use of power electronics in wind turbine systems has shifted from partial-scale to full-scale levels, bringing more flexibility and controllability into the system. Furthermore, to enhance the grid integration of renewable energy, multiport converters are being studied for integrating into energy storage devices [22]. Due to system cost limitations, these mainly focus on low-power grid-connected RESs.

With the relatively small installation capacity of renewable energy in the past, the motivation of the control strategies for RESs was to satisfy the grid-following demands, e.g., high power quality and grid synchronization [6], [9]. In present-day scenarios, grid-supportive control is increasingly in demand. Moreover, protection is mainly designed for ensuring the stable and safe operation of RESs, but not the grid. However, with the continuous increase in grid-connected renewable energy, the stability of the grid is challenged in some areas. Consequently, control strategies for large-scale grid-connected RESs are now focusing on grid-forming capabilities, to enhance grid resiliency [5]. Furthermore, the RESs coopted with power converters need to also intelligently respond to global management commands from system operators (e.g., limited power injection) as well as specific demands from the end-users (e.g., uninterrupted power supply). In addition, reliability-oriented control will be more significant in the consolidation of grid integration.

This paper provides an overview of the development of power electronics for efficient and reliable energy conversion from RESs, with a focus on wind and PV technologies. In Section II, the typical architecture of RESs is briefly introduced, followed by a comprehensive review of the demands on wind and PV power systems. Then, technologies for wind and PV power systems are reviewed in terms of converter topologies and control strategies, in Section III. In Section IV, challenges and research trends on future power electronics technologies for large-scale grid integration of RESs are presented. Finally, Section V gives the conclusions.

II. Requirements for RESs

A. Typical RES Architecture

A typical RES architecture is shown in Fig. 4, in which the power electronics converter is a critical interface to connect the renewable energy, the utility grid, the end-users, and even the energy storage devices. As shown in Fig. 4, the power electronics converter undertakes the mission of transferring varying amounts of renewable energy into the utility grid with a constant voltage amplitude and a fixed frequency, and/or provide energy to local users. Therefore, demands on power electronics are diverse and complex. It can be generally summarized as—1) harvesting the maximum energy possible according to the characteristics of renewable energy; 2) producing the most energy with the least cost through power converters (related to power semiconductor devices and topologies), i.e., being high efficiency, high power density, and low cost, along with high reliability; 3) grid supporting capability (e.g., flexible power control and power management). The specific demands for wind and PV power systems as well as certain grid integration requirements are discussed in the following.

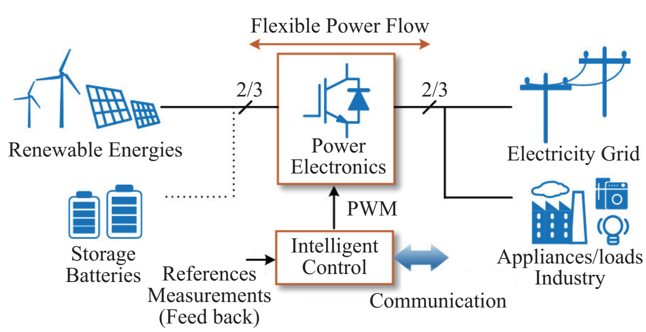

Fig. 4. Configuration of a typical grid-connected RES with power electronics converters and intelligent control.

B. Demands on Wind Power Systems

For wind power systems, a wind turbine harvests the wind energy as mechanical energy, and a generator converts it to electrical energy. Then, a power converter regulates the electrical energy to meet the requirements of the utility grid and/or local loads [23]–[25]. The specific demands on wind power systems are shown in Fig. 5, which can be summarized into three aspects:

1) *Wind generator side*: The generator rotor or stator current is controlled by the power electronics converter to regulate the electromagnetic torque of the generator. The demands of the generator side current control are not only to harvest the maximum energy but also to ensure energy balance when there is an inertia mismatch between the mechanical and the electrical power [23].

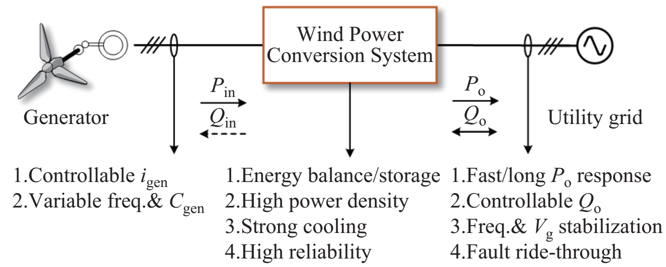

Fig. 5. Common demands on wind power systems, where P_{in} and Q_{in} are the active and reactive power transferred from the generator to the power converter, respectively, i_{gen} and V_{gen} are the generator current and voltage, respectively, P_{o} and Q_{o} are the active power and reactive power exchange between the power converter and the utility grid, respectively, and V_g is the grid voltage [11].

2) *Utility grid side*: The requirements for wind energy grid integration, including grid synchronization, response under abnormal grid conditions, and for grid supporting, aim to ensure safe operation with high integration of wind energy [5], [8], [26]. The most widely concerned demands are power quality, reactive power injection, frequency regulation, and fault ride-through operation. Furthermore, communication, power forecasting, ramp rate limitation, and other requirements are seen in practice as far as offshore wind power plants are concerned [27].

3) *Wind power conversion system side*: As the power conversion system is the core of the wind power system, failures at the power conversion stage will affect the entire system operation and lead to high maintenance costs, especially with a relatively large wind power capacity. Therefore, reliability becomes increasingly significant in wind power systems [28], [29]. Furthermore, to ensure normal power transmission when connected to the grid, a transformer is usually adopted to boost the voltage level. In this case, power density and heat dissipation issues should be well addressed due to the limited physical space of the nacelle and tower in wind power systems. Moreover, energy storage/balancing capability should be integrated into the power conversion stage to avoid additional costs caused by the power mismatch between the wind turbine and the utility grid in the very short term [23], [30].

C. Demands on PV Power Systems

Solar PV energy is directly obtained through PV cells/panels using the *photovoltaic effect* in PV power systems without any mechanical energy conversion stage as in the case of wind power systems. As a result, the demands on PV power systems are less rigorous than those on wind power systems, although far stricter requirements need to be complied with due to the remarkable expansion of solar PV installation [31]–[34]. The demands for PV power systems can be categorized as shown in Fig. 6.

(1) *PV panels side*: Maximum energy harvesting and good maintenance of the PV panels (i.e., PV panel monitoring) should be ensured to enhance high energy utilization as well as a long lifetime of the system. Generally, a DC-DC converter

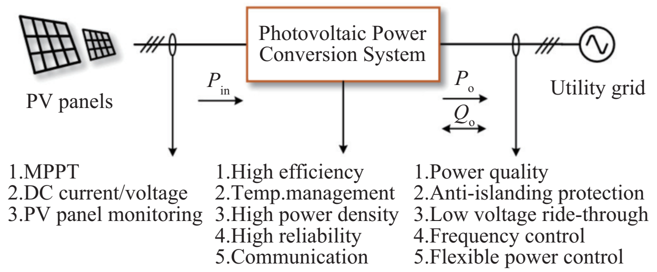

Fig. 6. Common demands on PV systems, where P_{in} is the active power from the PV panels to the power converter, and P_{o} and Q_{o} are the active and reactive power injected into the grid.

employed as the first stage of PV inverters enhances the flexibility of power tracking [31]. Also, it extends the operation hours to some extent.

(2) *Utility grid side*: The requirements of PV systems have also been enhanced in terms of power quality, voltage/frequency regulation, and abnormal grid voltage protection and recovery, as illustrated in Fig. 6. For instance, the total harmonic distortion (THD) of the grid current must be lower than 5% [7], [12], [32]. Moreover, many of the existing grid-supporting demands in wind power systems have now become mandatory for PV systems, as the power capacity is increasing. For example, low-voltage ride-through (LVRT), frequency regulation and reactive power injection demands are now seen in IEEE Std. 1547–2018 (i.e., revision of IEEE Std. 1547–2003) [5], [35]–[38].

(3) *PV power conversion system side*: Although the price of PV panels is continuously decreasing, the cost-efficiency of the power capacity per generating unit in PV systems is relatively low. Lowering the overall costs while increasing the efficiency in power converters should be specially considered. The transformer-less PV inverters at low power levels are promising alternatives with high efficiency as well as high power density [31], [39]. In this case, the leakage current issue becomes critical due to the parasitic capacitance between the PV panels [5][26]and the ground. Accordingly, grid codes in [6] and [40] require that the leakage current should be suppressed below the limit (e.g., the root mean square (RMS) value should be lower than 300 mA) to ensure the safety of equipment and personnel. It is worth noting that reliability, which directly affects the stable operation and indirectly the system cost, becomes more important in power electronics for PV systems [41], [42]. Since the PV inverter is always being exposed to harsh environments or smaller housing, thermal management should be considered to enhance reliability.

D. Grid Integration Requirements

It is well known that the most inherent characteristic of wind and solar energy is weather dependency, which means uncertainty and unpredictability are expected. To alleviate the impact of intermittency, the RESs, e.g., wind and PV power systems, should support the grid [11]. The main pathway includes predicting power production, flexible power control capability, and fast dynamics to the varying weather and operation conditions.

For instance, an unexpected disconnection may be triggered by a sudden grid voltage decrease, threatening the equipment and grid security, or even leading to a large-scale outage under a high-level penetration of renewable sources. To tackle this, the RESs must remain connected during this short period, which is exemplified as the mandatory ride-through operation area in Fig. 7. Figure 7 demonstrates the response time and voltage ride-through requirements for distributed energy resources (DERs) (including wind and solar PV energies) in IEEE Std. 1547–2018 [5]. It can be illustrated that the response for the abnormal voltage conditions becomes more flexible and controllable.

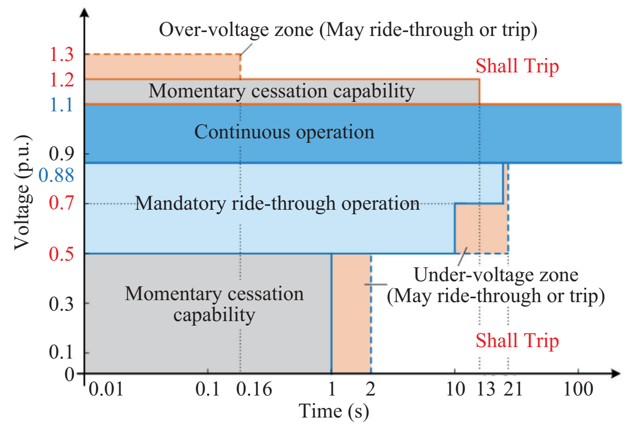

Fig. 7. Response for distributed energy resources (DERs) to abnormal grid voltages in the IEEE Std. 1547–2018 [5], including voltage ride-through requirements.

Furthermore, the RESs should have voltage/frequency support during the fault ride-through operation, including voltage-reactive power regulation and frequency-active power regulation [5], [32]. More specifically, in the case of LVRT operation, RESs can operate as per one of the following regulation modes of reactive power: 1) constant power factor mode; 2) voltage-reactive power mode; 3) active power-reactive power mode; and 4) constant reactive power mode [5]. Moreover, the transmission system operator can send commands for the reactive power injection to regulate and support the grid voltage. Notably, this reactive power control should be realized slowly (e.g., under the time constant of minutes) in steady state. Referring to the requirements for the active power, the RESs should regulate the active power according to the grid frequency at the Point-of-Common-Coupling (PCC). As exemplified in Fig. 8, the production of the wind turbine can be limited to any power setpoint remotely. When the production is 100% of the rated power, the frequency control can only reduce the output power for over-frequency events (i.e., the red line in Fig. 8). In contrast, when the wind turbine operates with a certain level of power reduction, the output power can both be increased and decreased to regulate the frequency flexibly (i.e., the blue curve in Fig. 8) [26]. It means that the wind power systems with reduced output power operation can provide more flexible grid frequency regulation. In all, grid codes in many countries have been modified to ensure stronger grid-supported capability of renewable energy systems, promoting reliable and stable large-scale grid integration.

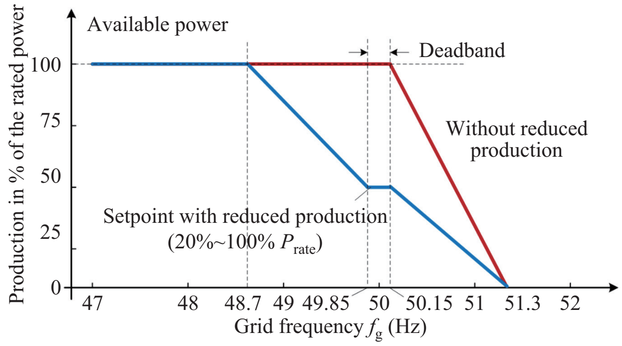

Fig. 8. Frequency regulation requirements for wind turbines connected to the grid [26], where f_g represents the grid frequency, and the wind turbine production can be limited to any power setpoint in the range of 20% $\sim$ 100% of the rated power P_{rate}.

III. Power Electronics for RES Integration

As mentioned previously, the power electronics for RES grid integration should not only consider the inherent characteristics of renewable sources, but also the grid requirements and energy transmission/distribution demands. Furthermore, more end-users' preferences should be integrated to provide intelligent energy management, e.g., uninterrupted power supply. As one of the typical RESs, wind power systems have experienced a change from non-power-electronics-based concepts to full-scale power converter-based systems with the power rating per turbine being significantly increased [24], [43]. At the same time, the power electronics for PV systems have had a remarkable evolution in terms of topologies and control strategies [31], [44]–[47]. Especially, reliability-oriented control and inertia enhancement strategies have been popularly researched for both large-scale wind and solar PV power converters.

A. Wind Power Systems

1) System Configurations

There exist several wind power system concepts depending on the types of generators, power electronics, speed controllability, and the way in which the aerodynamic power flows. Correspondingly, the power converters are of various types and configurations in those wind power systems with different generators and power rating levels. As of now, the Doubly-Fed Induction Generator (DFIG) with partial-scale power converters is still the mainstream configuration of wind power systems, as presented in Fig. 9(a) [23]. To develop efficient, reliable, and compact wind turbine systems, full-scale power converter-based synchronous generators (SG)/permanent magnet synchronous generators (PMSG) or induction generators (IG) are playing an increasing role in the wind power system market, which is shown in Fig. 9(b). It is anticipated that the full-scale configuration will further cover the market of wind power systems in the future along with the fast development of power electronics [23], [28].

2) Power Converter Topologies

Depending on the wind turbine system concepts, the power converter topologies vary. For instance, the most common power converter in the DFIG wind power systems is the two-Level Voltage Source Converter (2L-VSC), which has a simple structure with a limited power rating [23]. As depicted in Fig. 10(a), the structure of a back-to-back (BTB) 2L-VSC is introduced, where the advantage is the full power controllability with a relatively simple structure and few components. This converter is a well-proven, robust, and reliable solution to low-voltage wind power systems.

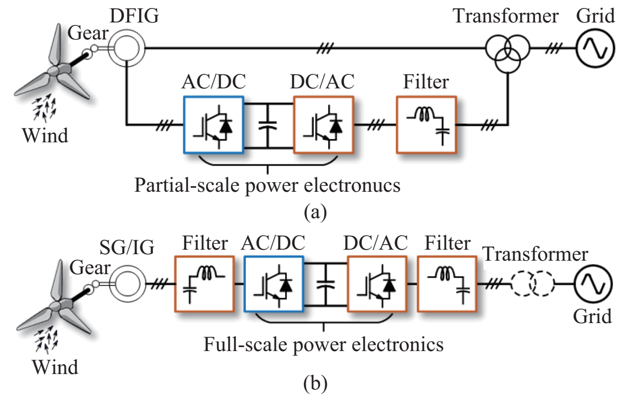

Fig. 9. Configurations of wind power systems based on variable speed wind turbines: (a) partial-scale power converter with a doubly fed induction generator (DFIG) and (b) full-scale power converter with a synchronous generator (SG)/induction generator (IG) [11].

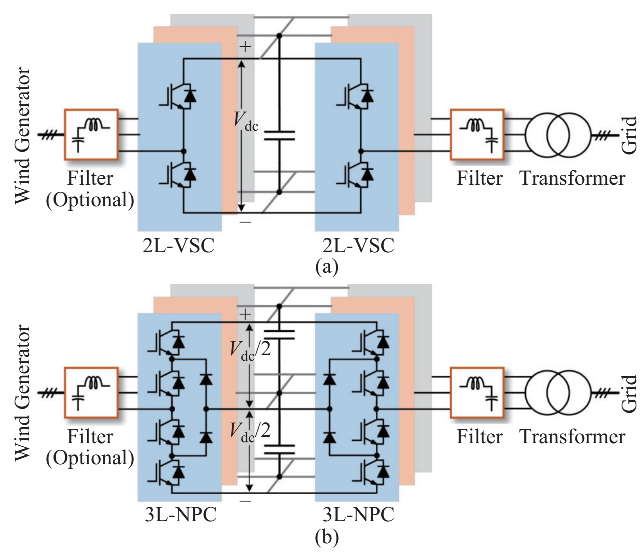

Fig. 10. Common power converters for wind power systems: (a) 2L-VSC back-to-back topology and (b) 3L-NPC back-to-back topology (Adapted according to the discussions in [23]).

Comparatively, multi-level power converters show promise for wind power systems with higher voltages and higher power ratings [24], [25]. A three-level Neutral Point Clamped (3L-NPC) BTB power converter is exemplified in Fig. 10 (b). Compared to the 2L-BTB converter, the 3L-NPC BTB topology can achieve less $\mathrm{d}v/\mathrm{d}t$ stresses on the semiconductor devices and smaller filter inductors due to the multi-level output voltages. In this case, multi-level power converters are suitable to achieve the medium-voltage (MV) level power conversion with lower currents. It is worth noting that the mid-point voltage fluctuation of the DC-link should be well addressed for reliable operation, as investigated in [25], [48].

With the continuous expansion of the installed capacity in wind power systems, multi-cell converter configurations (i.e., converter unit modules connected in the form of an array) are also becoming promising and will be used in wind turbine systems in the future as power levels increase [21], [49]–[51].

3) Control

For wind power systems where the time scales are different for various reasons, the mechanical turbine and the power converters need to be controlled [11]. According to the special demands in Fig. 5, the control of wind power systems typically includes three levels, as shown in Fig. 11. The control functions for the power converter system, i.e., the power interface between the wind turbine and the grid, are detailed as follows:

(1) *Basic control*: Like all grid-connected converters, the basic control for wind power converters mainly considers current regulation, stabilization of the DC-link voltage, and grid synchronization [9]. The most common control strategy is still the proportional-integral (PI) control, while proportional resonant (PR) control, repetitive control [52], and model predictive control are also used [53]. The objective of the basic control is to obtain efficient and reliable power conversion. In addition, the basic control should provide good steady-state and dynamic performances to ensure stable and safe operation.

(2) *Specific control*: Since the wind speed varies, the generated power also fluctuates. Therefore, the mechanical system and power converter should be properly controlled to maximize energy harvesting by adjusting the rotational speed of the turbine. When the wind speed is lower than the rated value, the wind turbine can find an optimal pitch angle to achieve power optimization. If the wind speed exceeds the rated value, the pitch angle should be regulated to limit the generated power, such as through frequency control utilizing the angle regulation presented in [54]. In the normal grid-connected operation, the wind power systems should adopt proper current controllers to meet the power quality requirements, where various advanced current control methods, e.g., sliding mode control [55] and observer-based state space control, have been studied for the voltage source inverters with LCL filters [56].

(3) *Advanced control*: Notably, many advanced control functions for wind power converters have been introduced to enable an intelligent, reliable, and grid-supportive system. For instance, reliability-oriented control may be considered to ensure high availability and low maintenance costs, lowering the cost of energy in a long run, such as thermal control and the reliability evaluation approach for the wind power converter with energy storage [57], [58]. Response to grid faults (e.g., voltage ride-through operation) and grid support capability (injecting or absorbing reactive power) should be provided to ensure grid-friendly wind power systems. Subsystems in the wind turbine, e.g., generator/grid side converters, braking chopper/crowbar, and pitch angle controller, also need to be coordinated to ride through abnormal grid conditions, such as power oscillation damping, inertia emulation, and grid voltage balancing [59]–[62].

B. PV Power Systems

1) System Configurations

Grid-connection PV configurations can be summarized into three types according to the power level, as presented in Fig. 12 [47], [63]. As shown in Fig. 12(a) and (b), considering an AC grid with the RMS voltage of 230 V per phase and the fundamental frequency of 50 Hz, the DC bus voltage for the two-stage PV inverters is typically 400 V for single-phase systems, and 700 V for three-phase systems, where a tradeoff between the power quality and switching stress is also taken into account. Referring to the central PV inverters in Fig. 12(c), a wide range of the DC bus voltages up to 1500 V is required for PV systems, to minimize the costs [64]. For low-power PV systems (e.g., below 1 kW), module-level converters are usually adopted to achieve the high MPPT efficiency of each PV panel, as demonstrated in Fig. 12(a). However, system costs are relatively high, and more power losses are generated when a large number of module converters with a high voltage gain are used.

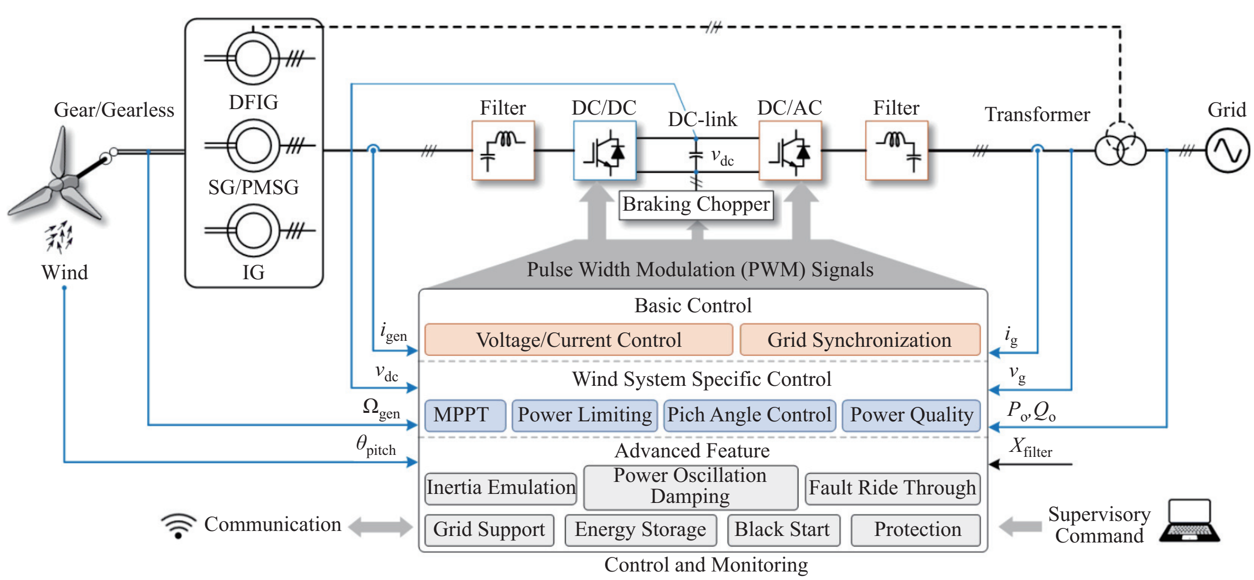

Fig. 11. General control structure for wind power systems.

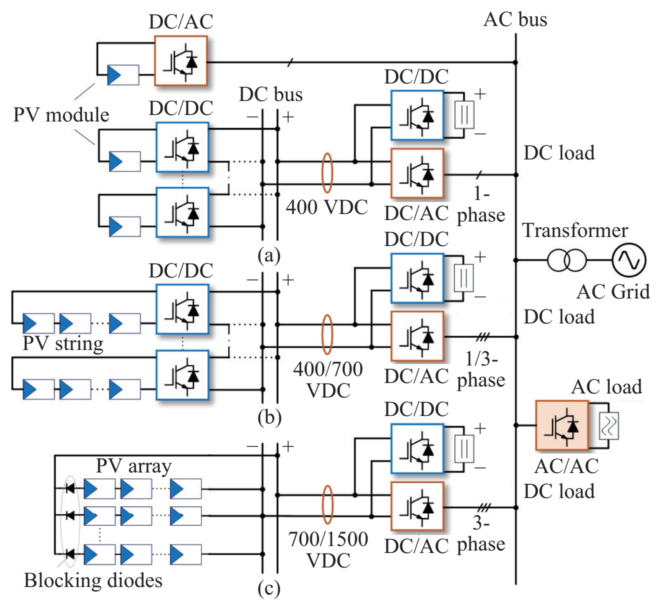

Fig. 12. Grid-connected PV configurations: (a) module-level converters for low-power applications (micro-inverter), (b) string inverters for medium or high-power PV systems, and (c) central inverters for utility-scale PV power stations, where optional DC-DC converters can provide a wide range of PV input voltages.

Consequently, string inverters are often preferred in residential and commercial grid-connected PV systems. The configuration of the string inverter is demonstrated in Fig. 12(b). Each string of PV panels employs a DC-DC power optimizer, and it is then connected to a string inverter. Although the MPPT efficiency for PV panels has to be compromised to a certain extent, the PV systems can obtain high cost-effective performances in terms of conversion efficiency, power density, reliability, and flexible control. Notably, multiple strings can be adopted to increase the overall system power.

For large-scale PV power systems (e.g., commercial and utility-scale PV stations), the central inverter is widely employed due to its simpler structure and control with lower overall system costs [47], as depicted in Fig. 12(c). For such a configuration, there are several challenges: (1) high voltage and current stresses on PV panels due to the high DC-link voltage and power level; (2) risk of low efficiency due to a global MPPT and mismatch of PV panels; and (3) lower reliability caused by the high-power diodes and one central inverter. To address the above issues, many central inverters adopt multi-level power converters for large-scale PV power systems with high voltage and high power, as well as parallel central inverters [65]. This may complicate the entire system to some extent.

2) *Power Converter Topologies*

Correspondingly, there are various inverter topologies in different grid-connected PV configurations, as shown in Fig. 14 [44]–[46], [65], [66]. As PV systems harvest solar PV energy through PV panels, the parasitic capacitor between the PV panel and the ground should be carefully considered in practice. All grid codes/requirements for PV systems have a strict limitation on the leakage current, e.g., the RMS leakage current limitation and sudden leakage current limitation according to DIN VDE 0126 [40], [45]. Generally, PV inverters can adopt transformers to provide isolation as they have low leakage currents, however, the overall system efficiency is low. Thus, transformer-less inverters have been introduced in the PV industry, where the leakage current issue must be well addressed [45].

Micro-inverters are increasingly used to directly interface PV modules to the utility grid [44], [66]. These can enhance the energy harvesting per PV module. Micro-inverters have to boost the PV module voltage for grid connection. High-frequency transformers are used in practice, such as the commercial inverters in [67]. On the other hand, many step-up transformer-less micro-inverters have also been introduced [44]. The buck-boost integrated full-bridge micro-inverter is illustrated in Fig. 13(a) [68].

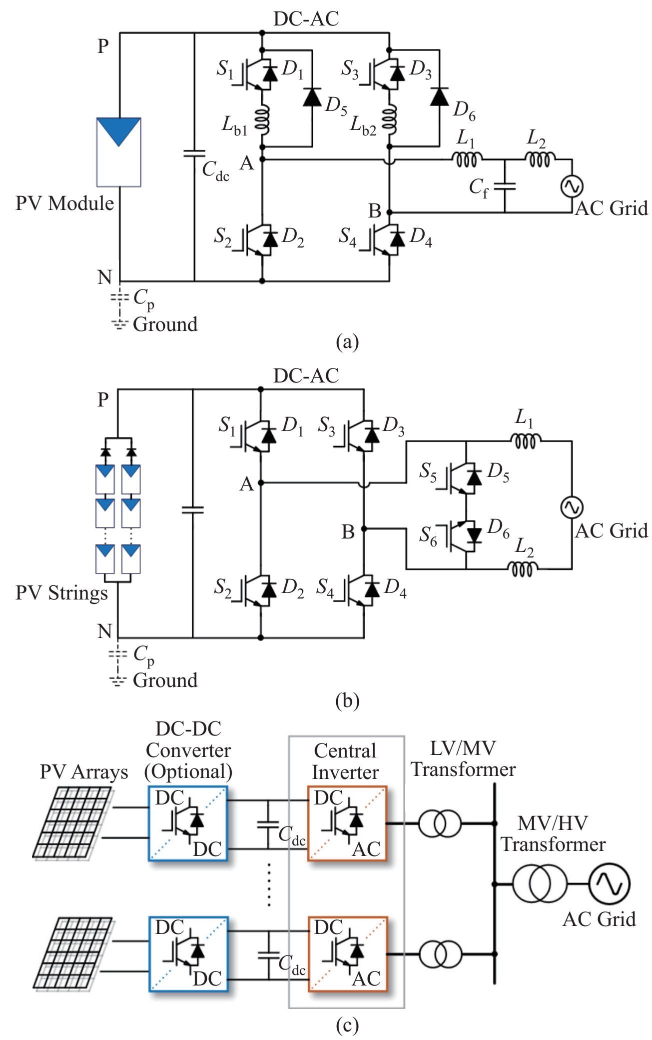

Fig. 13. Power converters for PV systems: (a) buck-boost integrated full-bridge micro-inverter, (b) transformer-less PV string inverter (HERIC), and (c) central PV inverters (3L-NPC).

To process high power while maintaining high efficiency, many advanced transformer-less inverters have been developed [45], [46] for PV strings. Transformer-less PV string inverters can be divided into two groups, i.e., DC-decoupling and AC-decoupling converters. For instance, the H5 inverter is

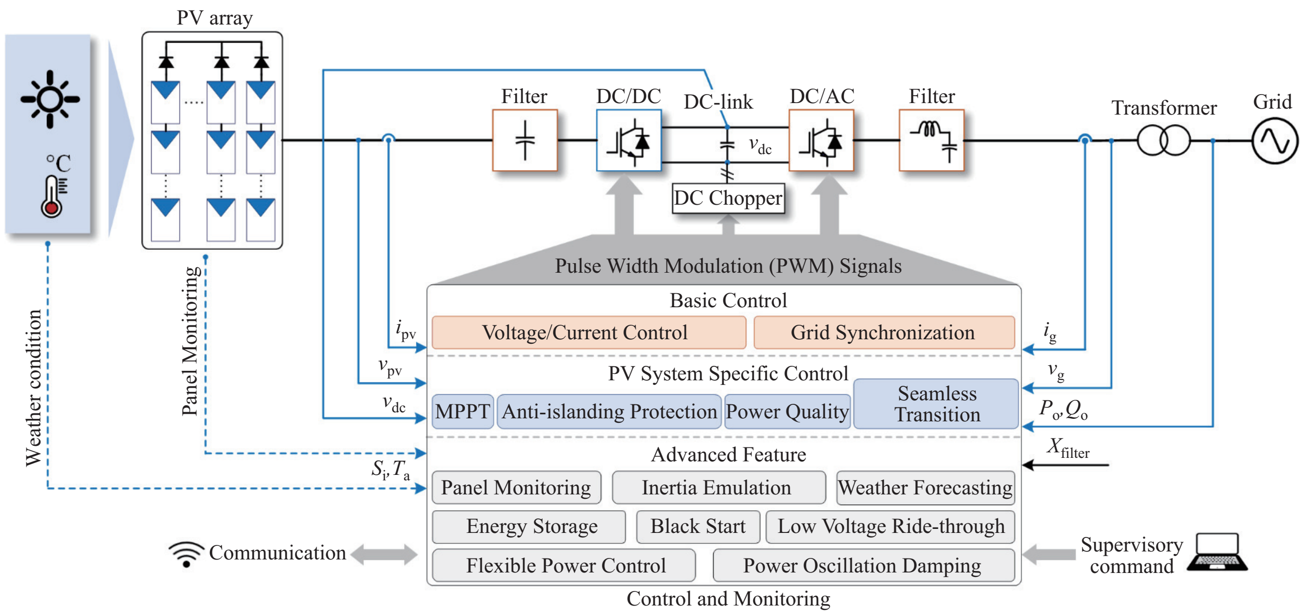

Fig. 14. General control structure for grid-connected PV systems.

a typical DC-decoupling inverter, however, its leakage current suppression is affected by the parasitic capacitors of the power switches [45]. The highly efficient and reliable inverter concept (HERIC), as shown in Fig. 13(b), is an excellent AC-decoupling topology with good performance in leakage current suppression, conversion efficiency, and reliability [69].

Several PV powerplants have come into service over several years that use central inverters (e.g., SMA Sunny Central CP XT inverter), and more are under construction. As mentioned previously, multilevel inverters are employed to tackle the issue of high voltage stresses, e.g., the 3L-NPC inverter adopted as the central PV inverter in Fig. 13(c) [65]. In addition, several central inverters are connected in parallel to share the current stresses and provide flexible power management. It should be noted that the line-frequency LV/MV transformers may be considered when being connected to the grid.

3) PV System Control

Most of the demands on PV systems depicted in Fig. 6 can be achieved by controlling the PV inverter. Especially with the remarkable growth in the installation capacity, more and more advanced features have had to be provided in addition to basic control of grid-connected inverters and PV system-specific control. The multi-layer control functions, as presented in Fig. 14, are detailed in the following:

(1) *Basic control*: As with wind power systems, the common basic control includes voltage/current control and grid synchronization, for which PI control, PR control, repetitive control, and model predictive control can be used [9], [52], [53]. Moreover, the basic control generally achieves good steady-state and dynamic performances, guaranteeing the power quality of the grid-connected PV system [70]. The basic controls are fundamental to PV system-specific controls and advanced features.

(2) *Specific control*: Power generation from solar PV systems is also uncertain and highly dependent on the weather/climate conditions. Thus, specific controls of the inverters adopted in PV systems contain the MPPT control, islanding protection, and seamless transition. In addition, the specific controls for wind systems are now mandatory in PV systems, as presented in IEEE 1547–2018 [5].

(3) *Advanced features*: Nowadays, reliability, fault ride-through, and grid supporting capability are emphasized in PV systems [71]–[77]. Correspondingly, more flexible power control is required [71], e.g., reactive power to regulate the grid voltage and active power to regulate the frequency. For example, the delta power production control and power reserved control are the recently studied active power control strategies for frequency regulation [72]. The inertia emulation can be achieved by either the virtual inertial control of the PV system or implemented by the integrated energy storage [73], [77]. To achieve long lifetime as well as high reliability, PV panels employ system-level condition monitoring schemes. Besides, reliability-oriented controls (e.g., power limiting control with weather forecasting and junction temperature control in the power modules [74]) are considered, to enhance the reliability and lifetime.

C. Grid Support

To realize the "carbon neutrality" strategy [1] and the sustainable energy transition, grid support capability is highly critical for achieving stable and reliable grid-integrated RESs. This means that the energy must be balanced between the generators and the loads under any conditions, such as uncertain and non-dispatchable renewables, abnormal grid conditions, and special demands from the operator or end-users. Consequently, many active and reactive power control strategies have been studied to improve grid integration [77]–[81]. For instance, the power references can be obtained intuitively through the power control based on the PQ theory [71]. Droop control with the reactive power injection function is usually adopted when the line impedance is inductive [81].

In addition to controlling the power generation of renewable energies [75], [80], the energy storage system is a feasible option to enhance the active power control capability [77]–[79]. In California, energy storage must be provided when installing grid-connected RESs [82]. To provide reactive power, the reactive power management capability has been integrated into RESs [81], [83]. Moreover, the centralized reactive power compensator is also a common device. As for reactive power compensators, the traditional methods are based on synchronous condensers and switch capacitors or inductors [84]. In contrast, more flexible and fast dynamics power electronics-based compensators are being developed, such as the static var compensator and thyristor-switched capacitors or reactors. Reactive/harmonic compensators with IGBTs are also being explored for high compactness, e.g., the transformer-less series compensator for HVDC transmission systems [85]. It is believed that more reliable and cost-effective power electronics will shortly be developed in power transmission applications. Figure 15 shows that wind and PV power systems adopt batteries and capacitors to achieve active and reactive power regulation, respectively. As demonstrated in Fig. 15, the distributed energy storage systems can be connected to both the DC-link and AC bus of wind and PV power systems by DC/DC converters or DC/AC converters, respectively. Recently, many stand-alone multiport converters have been developed to integrate energy storage batteries into RESs, achieving flexible configurations, high system efficiency, high power density, low device count, and simple control. Moreover, the centralized energy storage device and the reactive power compensator are directly connected to the AC grid. The above auxiliary devices, i.e., energy storage batteries and reactive power compensators in Fig. 15, can achieve an optimal operation point between cost and revenue growth [79]. In all, grid-friendly RESs have to minimize the impact on the grid operation, while also providing additional services.

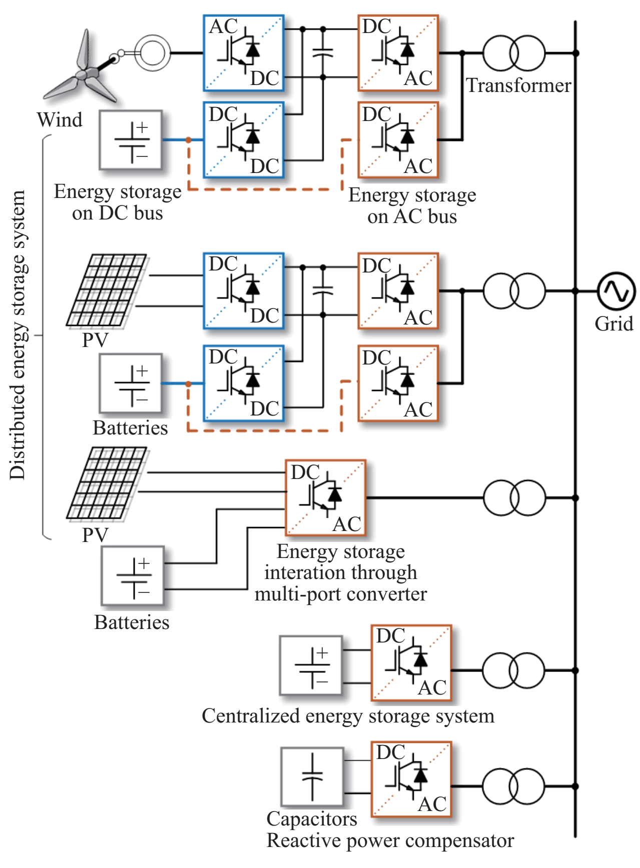

Fig. 15. Energy storage integration and reactive power compensator for grid support of wind and PV power systems.

IV. Trends in Power Electronics for RES Integration

A. Power Device Technologies

Power semiconductor devices are the key components to achieve energy conversion in terms of system cost, efficiency, power density, reliability, and modularity. The further development of power semiconductor devices can be summarized as follows:

(1) *Materials*: High-power silicon-based semiconductors have been the main components in power converters of RESs for several decades, e.g., IGBT and Integrated Gate Commutated Thyristor (IGCT). The development of WBG devices, e.g., SiC and GaN power devices, has led to more advantages as well as fresh challenges. On one hand, high switching frequencies and low power losses of WBG devices can improve the power density of power converters. On the other hand, challenges in the design of gate drivers and EMI issues should be considered, especially when the switching frequency of the WBG devices is becoming much higher, e.g., several MHz.

(2) *Packaging*: The conventional packaging technology for IGBT, which has soldering and bond-wire connection in their internal chips, has the disadvantages of large thermal resistance, low power density, and high failure rates [86], [87]. To increase the lifetime of the IGBT modules, improved technologies include press-pack-based plate soldering, sinter technology to avoid the chip soldering, as well as replacing the bond wire with new materials to reduce the coefficient of thermal expansion [88], [89]. The press-pack technology improves the connection of chips by directly press-packing the contact, leading to low short-circuit failure, high power density, and better cooling capability. Consequently, the press-pack devices, including the silicon-based and WBG devices, are expected to be utilized more widely in the future [90].

Packaging technologies are significantly relevant to the lifetime of power semiconductor devices, further affecting their applications in RESs. Power semiconductors for new power converters, which would need to meet the high power level demands of future large-scale grid-integrated RESs, would encounter much higher levels of voltage/current stress. In addition to thermal management, compactness, and failure rates, packaging technologies would require much higher performance in terms of parasitic parameters (e.g., especially for WBG devices with high switching frequencies), explosion resistance, and costs. Moreover, the better means of connection of power semiconductor devices in series or parallel is also an important aspect to handle high power and high currents.

B. Reliability

One of the main goals of power converters for RESs is to achieve the highest energy conversion efficiency with the lowest system cost. Therefore, high reliability has drawn more and more attention [28], [29], and this will continue in the future as RESs have to operate for 25 $\sim$ 30 years [14]. In addition to improving the power converter structure and developing more advanced semiconductor devices (e.g., WBG devices), reliability-oriented control strategies show promise in enhancing reliability and performance.

Reliability-oriented design and control, including effective thermal management, robustness design, and validation with the knowledge of mission profiles, are gaining much interest. For instance, many attempts have been made to develop the thermal models of power devices and power converters to estimate the lifetime of the system, thereby enabling the reliability-oriented design [58], [91]–[93]. Moreover, many control strategies have been developed that aim to improve thermal performance, such as junction temperature control during LVRT operation and hybrid control to reduce the thermal loading by flexible power regulation [91], [93]. Reliability will be considered more and more in future large-capacity renewable energy systems, and such reliability will be more and more dependent on power electronics.

C. Advanced Control

Deep integration of RESs and energy storage is an efficient path to realize energy balance, fault-tolerance, and grid support capability, and for tackling issues caused by renewable fluctuation and abnormal grid conditions [94]. In addition, RESs with energy storage can be considered as an energy hub in the concept of the Energy Internet, which features intelligent cooperation management with the end-users and operators [95], [96]. In this case, power electronics will be equipped with many advanced control strategies, enabling thermal analysis and control, and energy-cooperated control strategies (e.g., artificial intelligence-based and data-driven controls [97]). Figure 16 exemplifies an Energy Internet architecture, where the future power grid has a high penetration level of RESs. In such a system, all forms of energy storage must be integrated, including electric vehicles or stationary batteries. The infrastructure of the Energy Internet contains the physical energy (e.g., RESs and the utility grid operator) and information networks (e.g., communication, data, and control center). With comprehensive information and flexible power control capability, global, efficient, and optimal energy management can be achieved for better power generation, transmission, and distribution. With further integration of storage, the development of energy storage materials is now more and more important [98].

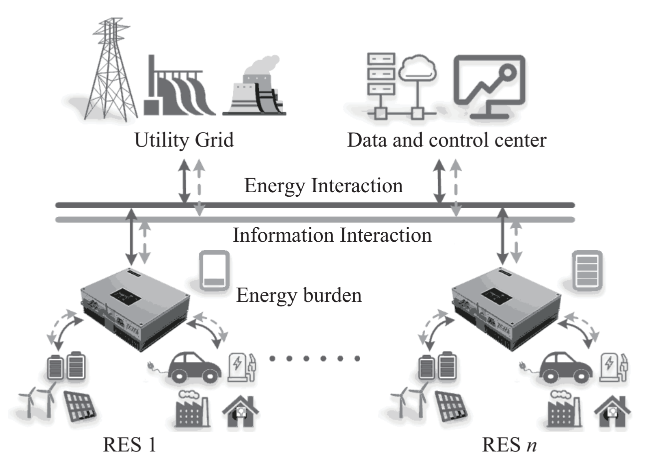

Fig. 16. Intelligent energy architecture for large-scale renewable energy grid integration.

D. Grid Integration

To continue the energy transition with large-scale RESs, more stringent demands in terms of grid integration, cooperation, protection, and end-user engagement are being made. This makes RESs with 100% power electronics operate in the grid-forming mode or become more flexible [99]. As illustrated in Fig. 16, these RESs (e.g., consisting of wind/PV energies, converters, storage devices, and loads) should consider the following aspects in the future:

(1) *Storage*: Without synchronous generators, RESs with 100% power electronics have low inertia, resulting in poorer voltage and frequency regulation capability. Thus, storage energy devices should be integrated with RESs to replace the role of synchronous generators in grid regulation. This energy storage can be provided either by using high-specific energy batteries, electric vehicles, and/or loads with certain energy storage [100], [101]. In this context, how to size the integrated energy storage devices in the design phase, and then how to better control the entire system to enhance the active/reactive power regulation capability to achieve enough inertia, are of interest in future power grids. Coordinative operation of multiple energy sources should be optimized to maximize the economic benefit.

(2) *Converters*: As shown in Fig. 16, power converters for RESs with grid-forming operational roles should integrate energy storage devices into RESs. Multiport converters are promising solutions that enable flexible power control, high system efficiency, high power density, and high reliability [22]. At the same time, many challenges, e.g., high power ratings and strong intermittency, should be considered when developing multiport converters for large-scale grid integration of RESs.

(3) *Control*: To realize the effective functional operation of RESs with 100% power electronics, the frequency and voltage controls may significantly differ from the grid-following ones. The power converters should be controlled to operate in the grid-forming mode, where the frequency and voltage control can be achieved as conveniently as that in the synchronous generators. In this case, the frequency and voltage control in the grid-forming mode should be properly addressed considering the stability of the utility grid and interaction with other loads and sources. Correspondingly, the operation range of the frequency and voltage, as well as future power systems' stability indices, may be redefined. Moreover, the cooperation and communication with the distribution/transmission operators should be re-prioritized according to the time scale. Com-

pared to the traditional grid-following RESs, the future grid-forming controls should be able to achieve fast and intelligent voltage/frequency control and realize power dispatch without communication. In this case, the coordinative operation needs to consider the impacts of voltage/frequency controls under grid-forming operation [99].

(4) *Resilience*: With large-scale RES integration, the unintentional disconnection of RESs will affect the stability of the grid (e.g., power outage). Thus, grid resilience should be enhanced if there are RESs connected to the grid, and there should be strong tolerance of faults, effective protection measures, and emergency management for quick recovery. For instance, the updated IEEE 1547–2018 requires voltage/frequency ride-through [5]. These fault-ride through operations and protections (e.g., current fault protections, anti-islanding protection, and power swing blocking protection) should be flexible and reasonably improved for the grid-forming operation of RESs with low inertia. Then, it becomes possible to minimize or ameliorate the disconnection incidents of RESs, thereby increasing the security of power supply from RESs. After the elimination of faults, the voltage regulation should be enhanced for grid voltage recovery under the large-scale integration of RESs (i.e., weak grid conditions).

All in all, with the further development of power electronics and the increasing demand for environmental-friendly energy generation, it can easily be anticipated that more and more RESs will be integrated into the power grid. In such an energy landscape, power electronics are analogous to the skeletons of human beings and underpinned by advanced control and information technologies, like the brain, and the grid integration will be more flexible and cost-effective. Eventually, it will help to reach global sustainability.

V. Conclusion

The development of renewable energy and power electronics (e.g., semiconductors and power converter systems) is explored in this paper. Among these, grid-connected wind and PV systems are the most common RESs. Before reviewing power electronics technologies, the stringent demands of present-day wind and PV power systems were summarized. Correspondingly, typical power converter topologies for wind and PV power systems, as well as general control strategies, were reviewed. The investigation illustrated that the performance of reliability, conversion efficiency, grid resilience, and system cost can be improved by enhancing the power converter topologies and control strategies. Finally, the challenges and research trends were discussed, i.e., power semiconductor devices (e.g., WBG devices), reliability aspects, advanced control, and system operation. To conclude, power electronics are playing an essential role (and will continue to do so) in the grid integration of renewable energy and in realizing the energy transition for a sustainable and green society. This will be underpinned by advanced control and information technologies.

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