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Power Electronics for Renewable Energy Systems – Status and Trends

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Abstract— **In the past few decades, the energy paradigms in many countries are experiencing significant change from fossil-based resources to cleaner renewables. It is expected that the scenario of highly penetrated renewables is going to be further enhanced. This requires that the production, distribution and use of the energy to be as technological efficient as possible, and incentives to save energy at the end-user should also be strengthened. In order to realize the transition smoothly and effectively, power conversion systems will continue to play an essential role. Using highly efficient power electronics in generation, transmission/distribution and end-user application, together with advanced controls, can pave the way for renewable energy resources. In view of this, some of the most promising renewable candidates like wind power and photovoltaic, which are becoming a significant part in the electricity production, are explored in this paper. Issues like technology demands, power converter topologies, and control structures are addressed. Some special focuses are also paid on the emerging trends in power electronics development for those systems.**

Keywords – power electronics; renewable energy systems; photovoltaic; wind turbine; reliability; advanced control;

I. INTRODUCTION

With an imperative demand of reliable and environmentally friendly electricity generation from Renewable Energy Systems (RESs), the total power generation of RESs is continuously booming and is going to be tripled within the next few decade [1]-[4]. Consequently, great efforts have been made by many countries (e.g. Germany, Spain, and Denmark) to introduce more renewable energies such as wind power, Photovoltaic (PV) power, hydropower, and biomass power. to be integrated into the electric grid. As it is shown in Fig. 1, among various renewable energies, Wind Turbine System (WTS) and PV system technologies are still the most promising technologies, accounting for a large portion of renewable energy generation [4]-[14]. However, the increasing adoption of RESs poses two major challenges, which are in urgent need to be coped with. One is the change of electrical power production from the conventional and fossil-based energy sources to renewable energy resources. The other one is the wide-scale use of power electronics in the power generation, the power transmission/ distribution and the end-user application.

The power electronics systems should be highly efficient and exceedingly reliable. As this technology has been the key to the energy conversion from the most emerging renewable energy sources, e.g. WTS and PV systems, it should be able to transfer the renewable energies to the power grid, and also capable to exhibit advanced ancillary functions (e.g. Low Voltage Ride-Through, grid support with reactive power injection). A wide-scale adoption of power electronics technology makes those completely weather-based energies more controllable, but increasingly intricate. Underpinned by intelligent control strategies, the power electronics technology can fulfill the requirements imposed by the distribution/ transmission system operators as well as the specific demands from the end-customers, especially when more advanced power devices and more accurate knowledge of the mission profiles are available.

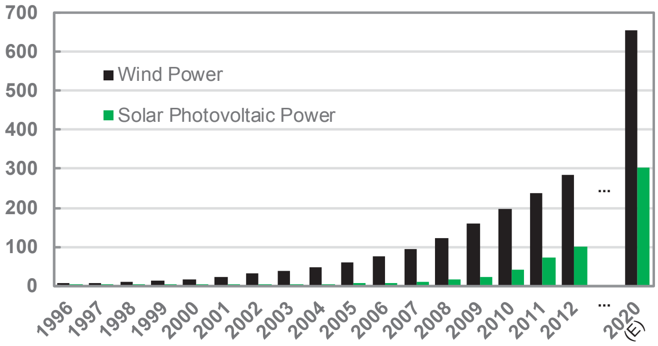


Fig. 1. Global cumulated wind power and solar photovoltaic capacity (Gigawatts) from 1996 to 2012, and an Estimation (E) by 2020 [1], [2].

In this paper, the status and the future trends in power electronics technology, which enables a clean and reliable power conversion from WTSs and PV systems, are discussed. In Section II, the basic demands of RESs are firstly presented, and followed by the WTS and PV technologies including main power converter topologies for both PV systems and WTSs. Then, typical control strategies for PV systems and wind turbines are presented by considering the grid demands. In Section III the focuses are paid on the converter concepts and topologies used in renewable energy systems. Finally, the future trends of power electronics for renewable energy application are given.

II. DEMANDS OF RENEWABLE ENERGY SYSTEMS

Fig. 2 demonstrates the architecture of a modern RES based power generation system, where the power electronics unit is the key component. An increasing penetration level of RESs results in more stringent grid demands. As it is shown in Fig. 2, the tasks of power electronics based RES are to manage the power demanding from the local operators as well as the end-customers [4], [5]. A very common demand of a RES is to transfer the energy to the grid based on the renewable energy characteristics. Other specific demands can be summarized as: a) reliable/secure power supply, b) high efficiency, low cost, small volume, and effective protection, c) control of active and reactive power injected into the grid, d) dynamic grid support (ride-through operation), and e) system monitoring and communication.

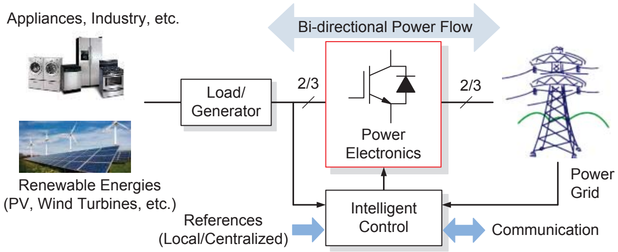


Fig. 2. Advanced modern power electronics technologies and intelligent control techniques for the renewable energy sources and loads.

A. Demands in Wind Turbine System

For the generator side, the current flowing in the generator rotor or stator should be regulated to control the electromagnetic torque, not only for maximizing the extracted power from the wind turbines, but also for the energy balancing in case of dynamics due to inertia mismatch between mechanical and electrical power. For the grid side, the converter must emulate the behaviors of conventional power plants regardless of the wind speed. This means it should help to maintain the frequency as well as voltage amplitude of the grid, and also withstand the grid faults or even contribute to the gird faults recovery [2], [16], [17].

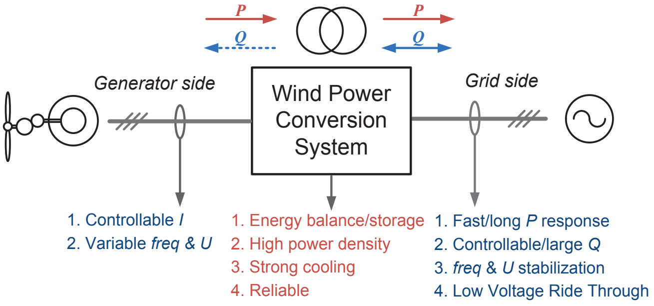


Fig. 3. Demands for modern wind power converters.

Due to relative large power capacity, the failures of wind power conversion system will impose strong impacts to grid stability and result in high cost to repair, thereby the reliability performance is especially emphasized. Also because of high power capacity, the voltage level of the generator may need to be boosted up to facilitate the power transmission, thus a transformer is normally required. Furthermore, because the space is limited in the nacelle or tower of the wind turbine, the power density and cooling ability are crucial performance for power conversion system. Finally because of the mismatch power inertia between the turbine and grid, energy storage and balancing is an important issue and may result in extra cost of the system.

B. Demands from the grid side

The fluctuation and unpredictable features of wind energy are non-preferred for grid operation. Most countries have strict requirements for the behavior of wind turbines, known as “grid codes” which are updated regularly [18]-[22]. Basically, the grid codes are always trying to make the WTS to act as a conventional power plant from the electrical utility point of view. That means the WTS should not only be a passive power source simply injecting available power from the wind, but also behave like an active generation unit, which can wisely manage the delivered active/reactive power according to the demands, and provide frequency/voltage support for the power grid. Examples of the state-of-the-art grid supporting requirements are given in the following. They are specified either for individual wind turbine or for the whole wind farm.

According to most grid codes, the individual wind turbines must be able to control the active power at the Point-of-Common-Coupling (PCC). Normally, the active power has to be regulated based on the grid frequency, e.g. in Denmark, Ireland and Germany, so that the grid frequency can be somehow maintained. As an example the characteristic of frequency supports in the Danish grid codes is shown in Fig. 12, where the active power should be decreased when the frequency rises above 48.7 Hz or 50.15 Hz depending on the power reserving strategy [21]. Similarly, the reactive power delivered by the WTS has also to be regulated in a certain range. As shown in Fig. 13, both the Danish and German grid codes give a range of the reactive power delivered by the WTS to the active power output [22] - this will lead to larger MVA capacity when designing the whole converter system. Also the Transmission System Operator (TSO) will normally specify the reactive power range of the wind turbine system according to the grid voltage levels. It is noted that this reactive power control should be realized slowly under the time constant of minutes in steady state operation [18].

Besides the normal operation, the TSOs in different countries have issued strict grid supporting requirements for the WTS under grid faults. As shown in Fig. 14, in which the boundaries with various grid voltage dip amplitudes as well as the allowable disturbing time are defined for a wind farm. It is becoming a need that the WTS should also provide reactive power (up to 100% current capacity) to contribute to the voltage recovery, when the grid voltage sag is present. Fig. 15 shows the required amount of reactive current against to the grid voltage amplitude by the German [22] and Danish grid codes [21]. This demand is relatively difficult to be met by the wind turbine concept in Fig. 4, and other power quality units like STATCOMs may probably be introduced to help the wind turbine system to achieve this tough requirement.

The requirements for more grid support by wind turbines on one hand have increased the cost per produced kWh, but on the other hand made the wind energy more suitable to be largely utilized and integrated into the power grid. It can be predicted that the stricter grid codes in the future will keep challenging the wind turbine system and also pushing forward the power electronic technologies.

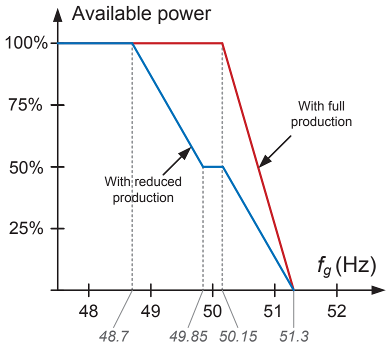


Fig. 4. Frequency control profiles for the wind turbines connected to the Danish grid [21].

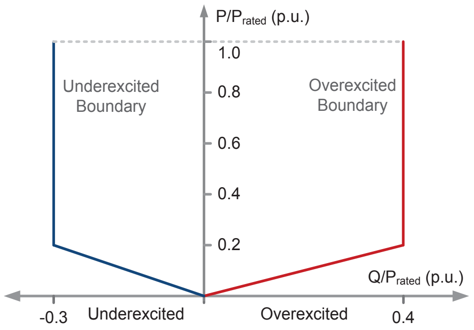


Fig. 5. Reactive power ranges under different generating powers for a wind farm specified by the German grid codes [22].

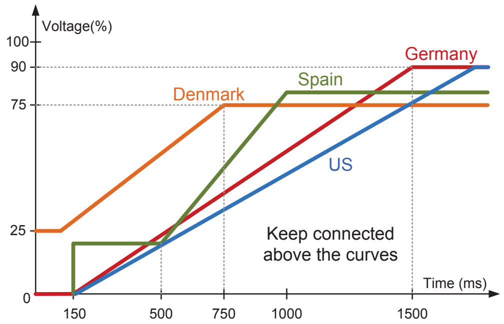


Fig. 6. Voltage profile for low voltage ride-through capability of wind turbines by different contries.

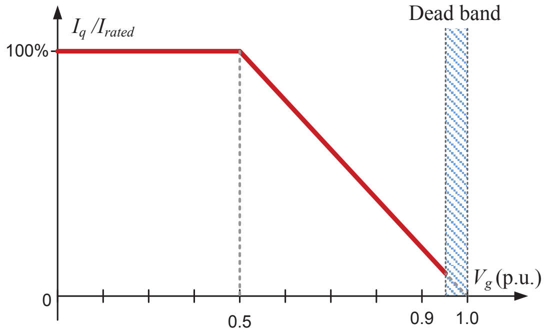


Fig. 7. Reactive current requirements for a wind farm during grid sags by the German and Danish grid codes.

C. Demands in PV system

Grid-connected PV systems are being developed very fast and will soon take a major part of electricity generation in some areas [53], [54]. Thus, the PV systems have to comply with much tougher requirements than ever before. These demands can be generally categorized into three parts as shown in **Error! Reference source not found.**. However, the ower capacity of a PV system (e.g. residential application, several kW) is not as large as that of an individual wind turbine system (e.g. several MW). Moreover, the power inertia of PV output is compatible with the behavior of power grid, and as a result the demands are less stringent when compared to wind turbine systems.

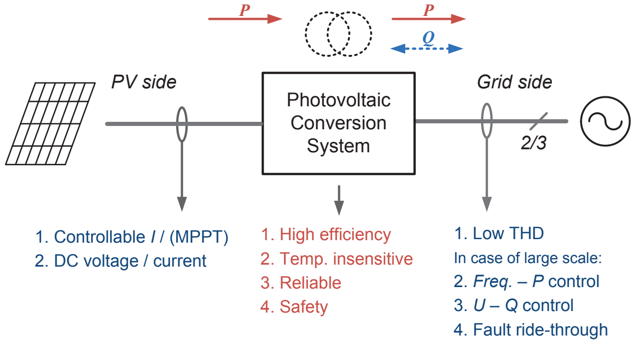


Fig. 8. Demands for PV power conversion system.

For the PV side, the current or voltage of the PV panels should be controlled to extract the solar energy. In view of this, a DC-DC converter is commonly used in PV power conversion systems to flexibly track the maximum power, strongly depending on the mission profiles. In this case, the DC voltage should be maintained as a desirable value for the inverter. For the grid side, normally the Total Harmonic Distortion (THD) of the output current has to be restrained at a lower level (e.g. 5%) [4]. While for large PV systems with higher power ratings (e.g. hundreds of kW), the grid side also demands the PV inverter to stabilize the grid voltage by providing ancillary services. In response to the grid faults, the PV inverters have to ride-through voltage faults, when a higher PV penetration level comes into reality [40]-[46]. Thus, the PV systems have to comply with the grid requirements similar with those for wind turbine systems, as it is shown in Fig. 6 and Fig. 7.

For the PV technology, the power capacity per generating unit is relative low but the cost of energy is relative high, and as a result there are very strong demands for high efficiency power conversion in order to achieve acceptable price per produced kWh. On the other hand, transformerless PV inverters have gained increasing popularity in the European market (e.g. Germany and Spain) [4], [55] in order to further extend the conversion efficiency. However, in this case the safety becomes a more crucial issue because of the lack of galvanic isolation in transformerless PV systems. Reduction of the potential leakage current is generally required.

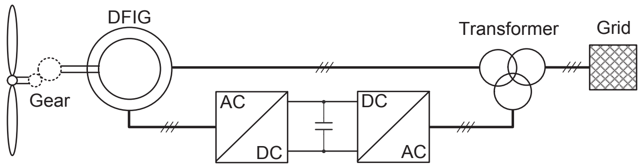
Furthermore, similar to the wind power conversion systems, reliability is important for power electronics based PV systems, and motivated by extending the total energy production (service time) and reducing the cost of energy. Finally, because of exposure or smaller housing chamber, the PV converter system must be more temperature insensitive, which is beneficial for the reliability performance.

III. Power Converter Topologies and Devices for Reneable Energy Applications

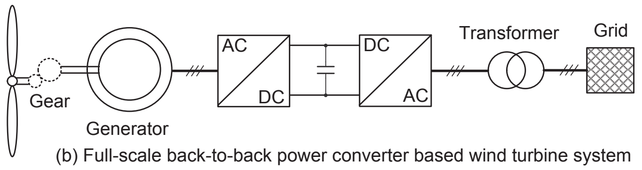
The design and operation of power electronics converters for both wind turbine and PV systems strongly rely on the grid requirements and the energy demand. It can be seen from the evolution of wind turbine power converters, which has changed from non-power-electronics-based topologies to full-scale power converters with increasing power ratings of individual wind turbine (tens of kW to several MW) [4], [8]-[10], [12]. As the demand of higher power ratings and efficiency increases for PV systems, the PV power converters also had an obvious change, and they are mostly transformerless nowadays [4], [6], [7].

A. Wind turbine system

For WTSs, the most commonly used design concepts can be categorized into four types: 1) fixed speed wind turbine systems, 2) partial variable speed wind turbine with variable rotor resistance, 3) variable speed wind turbine with partial-scale frequency converter, and 4) variable speed wind turbine with full-scale power converter. Among those WTS configurations, the latter two types are currently dominant in the markets and they are shown in Fig. 9. Moreover, the two concepts are expected to be even more widely adopted in the future.



(a) Partial-scale back-to-back power converter based wind turbine system



(b) Full-scale back-to-back power converter based wind turbine system

Fig. 9. Two dominant power electronics based WTS configurations.

As it is indicated in Fig. 9, the power electronics technology plays an essential role in those two concepts. Regarding the power converter topologies for wind power applications, the most commonly adopted three-phase converter is the two-level Voltage Source Converter (2L-VSC), featuring with simple structure and few components, as it is shown in Fig. 10. However, since the power capacity of an individual wind turbine keeps growing up to even 10 MW [13], [14], the 2L-VSC is not very feasible due to lower efficiency. In view of this, the multi-level converter technology, which can achieve more output voltage levels, higher voltage and larger output power, gains much more popularity in the wind turbine applications [9], [10], [13]-[16].

The most commercialized multi-level converter is the three-level Neutral Point diode Clamped (3L-NPC) topology shown in Fig. 11. Compared to the 2L-VSC, 3L-NPC can achieve one more output voltage level, thus leading to a smaller filter. The major drawback of this converter is the unequal loss distribution between the inner and outer switching devices, which may contribute to a de-rated converter power capacity [14], [15]. To solve this problem, multi-cell converter topologies (i.e. parallel/ series connection of converter cells) are developed and widely adopted by the industries (e.g. Gamesa and Siemens) [17], [23].

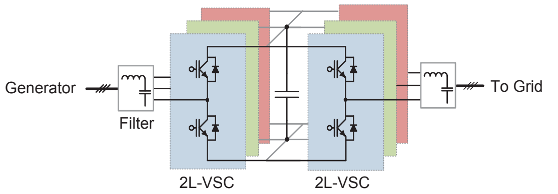


Fig. 10. 2L-VSC Back-to-Back (2L-VSC BTB) converter for WTS.

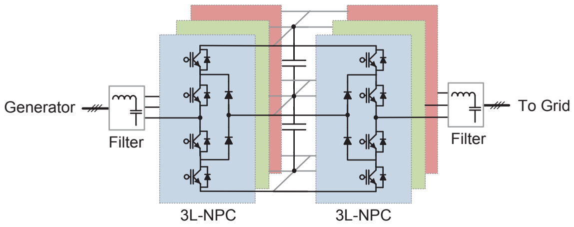


Fig. 11. 3L-NPC Back-to-Back (3L-NPC BTB) converter for WTS.

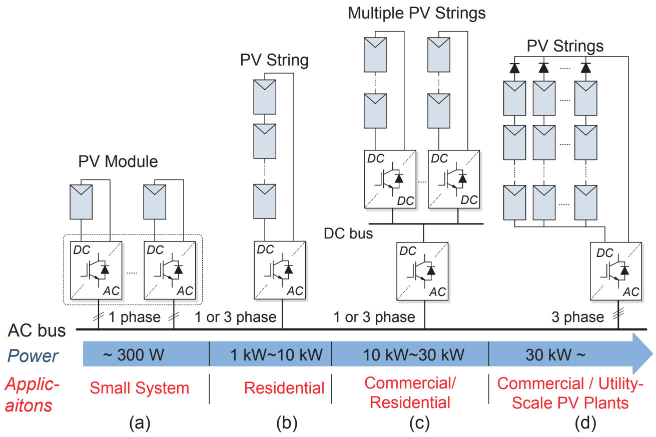


Fig. 12. Grid-connected PV systems with: (a) module inverter, (b) string inverter, (c) multi-string inverter, and (d) central inverter [6].

B. Photovatic system

For PV systems, a general classification of grid-connected PV inverters is shown in Fig. 12. A common central inverter can be used in a PV plant larger than tens of kWp with higher efficiency and lower cost. Its major disadvantages are high voltage DC cables, common Maximum Power Point Tracking (MPPT) and module mismatch [6]. Compared to central inverters, the string inverter can achieve MPPT separately, leading to a better total energy yield. However, there are mismatches in the PV panels connected in series. Thus, the module inverter is developed, which acts on a single PV panel with a single MPPT. The main disadvantage of a module inverter is the low overall efficiency. Another PV technology is an intermediate solution between the string inverter and the module inverter, being a multi-string inverter. This configuration is flexible with a high overall efficiency because each PV string is controlled separately.

In contrast to WTSs, the PV systems are still dominant in residential applications with much lower power ratings (e.g. several kWp), as it is shown in Fig. 12. Thus, at present, single-phase topologies are more common for the PV applications. Normally, in those cases, DC/DC converters are adopted to boost up the PV voltage within an acceptable range of the PV inverter. The boost converter also offers the flexibility of extracting the maximum power. However, several PV power plants have come into service recently using central inverters (e.g. SMA Sunny Central CP XT inverter) and more are under construction, due to an intense energy demand and carbon dioxide emission reduction. The power converter technology for this is similar to the grid side converter technology in WTSs.

When it comes to the design of PV inverters as well as their related control methods, the efficiency and leakage current are two main considerations. Connecting the PV inverters to the grid through isolation transformers can solve the safety issues due to the leakage current, but leading to a lower efficiency and a more bulky system. Thus, transformerless PV inverters are developed [4], [6], [7], [24]-[30] by considering the leakage current issue and they have gained much more popularity especially in the European markets. A widely adopted single-phase PV inverter is the Full-Bridge (FB) topology as shown in Fig. 13. Two main modulation schemes are available for the FB inverter - unipolar modulation and bipolar modulation. In the light of safety issues, the FB with bipolar modulation is more feasible in the single-phase transformer-less PV applications. However, the conversion efficiency is not very satisfying.

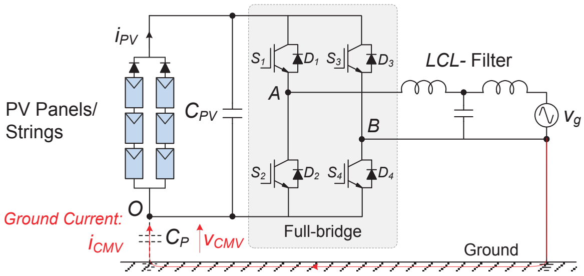
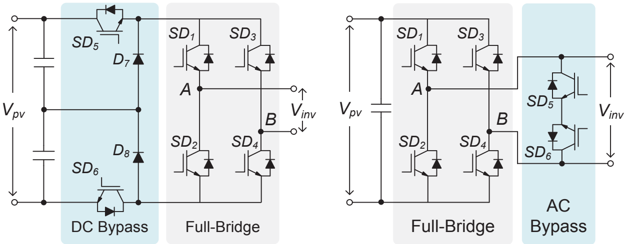


Fig. 13. Single-phase full-bridge PV inverter with an *LCL*-filter.

Many other transformerless PV inverters available on the markets are derived from the FB topology. For instance, the H6 inverter patented by Ingeteam [25] shown in Fig. 14 disconnects the PV panels/strings from the inverter using four extra devices to realize the "isolation"; while the Highly Efficient and Reliable Inverter Concept (HERIC inverter) by Sunways [27] provides an AC bypass. There have been other topologies reported in the literature, [7], [28]-[30]. An example shown in Fig. 15 is based on the Neutral Point Clamped (NPC) technology.

Although single-phase configurations are more common for PV applications, some companies like SMA, Sunways, and Kaco are promoting the three-phase PV systems with central inverters for utility-scale applications [56]-[58]. Those large PV power plants, rated over tens and even hundreds of MW, adopt many central inverters with the power rating of up to 900 kW. A typical large-scale PV power plant is shown in Fig. 16, where DC-DC converters are also used before the central inverters. It is worth mentioning that for those high power PV applications, the NPC topology might be a promising solution to the realization of large-scale PV systems.



(a) H6 inverter

(b) HERIC inverter

Fig. 14. Two transformerless PV inverters (H6 and HERIC) [25], [27].

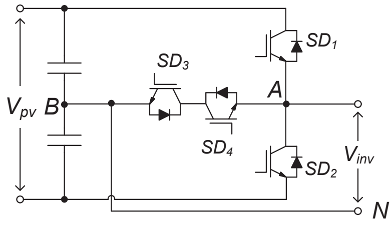


Fig. 15. Neutral point clamped transformerless topology for PV application.

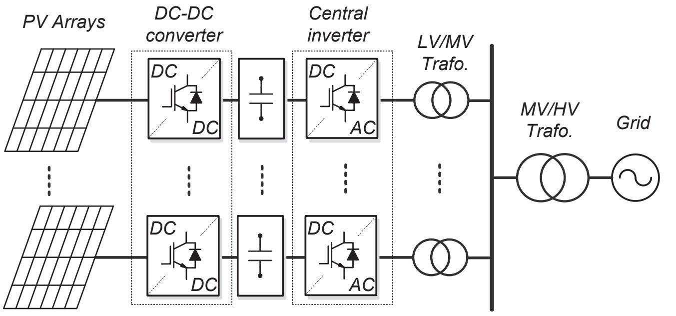


Fig. 16. Typical large-scale PV power plant based on central inverter for utility applications.

C. Power devices for wind and PV system

The power semiconductors are the backbone in the power electronics technology and will determine many critical performances of the renewable energy system like the cost, efficiency, reliability, modularity. The potential silicon based semiconductor technologies in the wind power application are among the module packaged *Insulated Gate Bipolar Transistor* (IGBT), press-pack packaged IGBT and the press-pack packaging *Integrated Gate Commutated Thyristor* (IGCT) [31]-[35]. While in the PV application, the module packaged IGBT and *Metal Oxide Semiconductor Field Effect Transistor* (MOSFET) are widely seen.

Recently there is a fast development of Silicon Carbide (SiC) based devices which are majorly in the form of MOSFET as well as diodes, although mainly targeted for low power applications like photovoltaic, they could be also the potential power devices used to build converter cells in wind power system. Another emerging power device based on Gallium Nitride (GaN) is also drawn a lot of attention recently due to the advantages of higher switching speed and further compacted power density, which are suitable features for the PV application.

Different types of power semiconductor devices have quite different characteristics and four of them are compared in Table I. The module packaging technology of IGBT has a longer track record of applications and fewer mounting regulations. However, because of the soldering and bond-wire connection of internal chips, module packaging devices may suffer from larger thermal resistance, lower power density and higher failure rates [34]. The main trends to improve the packaging technology of IGBT module are to introduce pressure contact to eliminate the base plate and thus base plate soldering, sinter technology to avoid the chip soldering, as well as replaced bond wire material to reduce the coefficient of thermal expansion – all lead to increased lifetime of module packaging IGBTs as reported in [35].

Table I. Power semiconductor devices for wind power application.

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

The press-pack packaging technology improves the connection of chips by direct press-pack contacting, which leads to improved reliability, higher power density (easier stacking for series connection) and better cooling capability. Press-pack IGCTs were first introduced into the medium-voltage motor drives in the 1990's and has already become state-of-the-art technology in the applications of oil, gas, HVDC, power quality, etc. However IGCTs have not yet been mass adopted in the wind turbine system. As the power capacity of wind turbines grows up even to 10 MW, it can be expected that the press pack packaging devices may become more promising solution for the future wind turbine system. However the total cost of the systems are the determining factors in this technology shift.

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

IV. CONTROL OF RENEWABLE ENERGY SYSTEMS

The first priority of the RES control is to extract as much energy as possible for the renewable energies in normal operation, which is known as Maximum Power Point Tracking (MPPT). As the penetration level of RESs continues to grow, many specific grid requirements have been imposed on those systems. It is further better for the RESs to provide ancillary services, such as LVRT, reactive power control and frequency control through active power control, in order to ensure a reliable and efficient power conversion from such renewable energies. For example, in Germany, the medium- and/or high-voltage systems should have LVRT capability with reactive power injection [4], [5], [10], [36], [38], and in Italy, similar requirement has been published and acted on low power rating systems (6 kW) [37].

Hence, it can be seen that the Distribution/Transmission System Operators (DSO/TSO) have given priority to finding a solution in order to guarantee stable operation of RESs and accept more renewable energies. This consideration should be taken into account, which makes the control systems of RESs

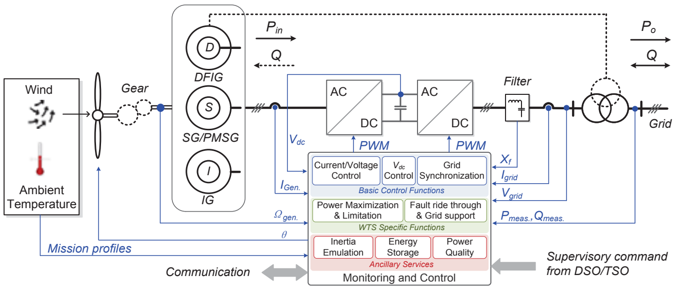


Fig. 17. General control function blocks for modern wind turbine systems.

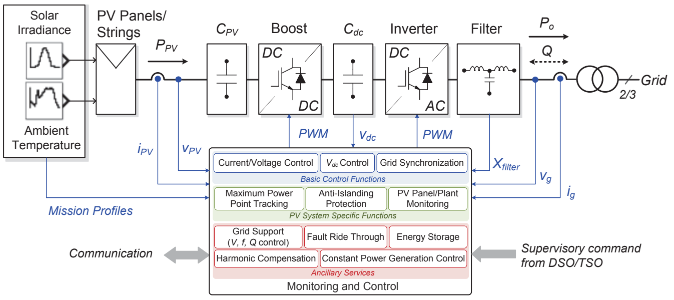


Fig. 18. General control function blocks of a typical PV system with a DC/DC boost stage.

multi-functional, as shown in Fig. 17. The basic controls like current regulation, DC bus stabilization and grid synchronization have to be quickly performed by the power converter, where a Proportional-Integral (PI) controller and Proportional-Resonant (PR) controllers are typically used [5].

Some advanced control functions of RESs, e.g. riding through operation of the grid faults and providing grid-support functions, are needed for both WTSs and PV systems as shown in Fig. 17. In the variable speed wind turbine concept, the current in the generator will typically be changed by controlling the generator side converter, and thereby the rotational speed of turbine can be adjusted to achieve maximum power production based on the available wind power. In respect to operation under grid fault, coordinated control of several subsystems in the wind turbine such as the generator/grid side converters, braking chopper/ crowbar and pitch angle controller, is necessary in order to handle the situation properly.

For the reactive power injection during LVRT operation in WTS applications, there are at least four major strategies available [4], [5], [38]-[42]: 1) unity power factor control, 2) positive and negative sequence control, 3) constant active power control and 4) constant reactive power control. Unbalanced grid faults are one of the most observed faults in three-phase systems. Since there is an interaction between voltage sequences and current sequences under grid faults, either the controlled active power or the controlled reactive power will give oscillations.

As the PV systems are still at residential level in respect to single-phase systems, there are less control freedom (grid voltage and grid current) under grid faults. Typically, they are required to cease energizing local loads under grid faults, known as anti-islanding protection. However, the penetration level increases the necessity of LVRT with reactive power injection [43]-[45]. By considering the over-current protection of PV inverters and the reactive current injection requirements under grid faults, possibilities for reactive power injection of single-phase PV systems can be [46]: 1) constant peak current strategy, 2) constant average active power strategy, 3) constant active current strategy, and 4) thermal optimized strategy. As for the three-phase PV systems, the control under grid faults is similar to that of the grid side converter in a wind power system, and thus the above strategies can be adopted and implemented in different reference frames [4], [5].

The injected current into the grid has to be synchronized well with the grid voltage, as standards require that in the field [4]-[6]. Therefore, the grid synchronization issue plays an important role for both WTSs and PV systems. To address this problem, Phase Locked Loop (PLL) based synchronization methods stand out of various reported solutions [5]. Evaluating criterions for the synchronization methods are the dynamic response speed and the disturbance rejection capability. The Second Order Generalized Integrator based PLL (SOGI-PLL) presents a better performance compared to other methods, especially for single-phase systems [4], [5]. It can be a good candidate for the synchronization for RESs and used in industrial applications.

Moreover, in respect to the aforementioned control methods for WTSs and PV systems, a fast and accurate synchronization system will strongly contribute to the dynamic performance and the stability margin of the whole control systems. The knowledge of grid conditions significantly affects the control systems in different operation modes. For example, the detection of the grid faults and the extraction of positive and negative sequence currents are of importance for the control of RESs in LVRT operation modes.

V. FUTURE TRENDS IN POWER ELETRONICS FOR RESS

As the heart of every renewable energy generation system, the power electronics converter is responsible for the power generation from wind and solar energy efficiently and reliability. Thus, to realize a widespread adoption of such renewables, the power electronics technology will be more active into the grid in the future. Together with advanced control strategies, it can fulfill the upcoming stringent requirements regarding the efficiency, the controllability, the cost and the reliability.

A. More Power Electronics

In the last few decades, the power electronics technology has become more and more advanced and brought significant improvements for the renewable energy generation [8]-[10], [47]- [49]. Together with intelligent control strategies, modern power electronics technology makes RESs more controllable and as active as the conventional power plants. There will more advanced power electronics systems in the future RESs in order to enable a better and flexible integration with the power grid.

For instance, it can be seen from the evolution of the wind turbine technology in **Error! Reference source not found.** hat the power electronics converter has already achieved 100 % power coverage in the wind turbine system since 2005, while the PV systems have already been complete power-electronics-based systems. Fully power-electronics-based wind turbine technology will be further enhanced by advanced control strategies. Actually, in most of the newly established WTSs, power electronics converters have become essential components carrying all of the generated power up to multi-MW [5]-[9].

B. More Stringent Grid Requiements

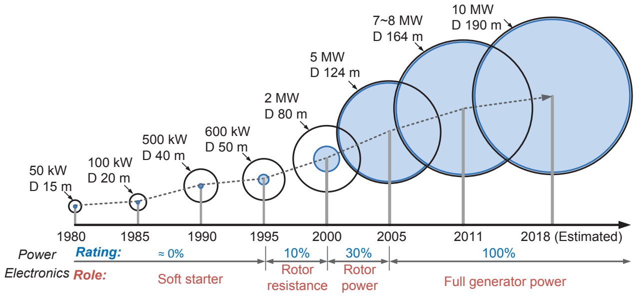


Fig. 19. Evolution of wind turbine size and the power electronics seen from 1980 to 2018 (Estimated), where the blue circle indicates the power coverage by power electronics.

In order to accept more renewables in the grid, the conventional power grid, which is normally based on centralized and large power plants, have to be modified to be more distributed and smaller generation units. Thus, new demands for grid integration standards, communication, power flow control, and protection are needed [10]-[12]. Power electronic converters together with dedicated and intelligent control strategies again play an important role in this technology transformation.

Taking the PV systems as an example, typically, MPPT is required during the operation. However, recent studies showed that a limitation of the maximum feed-in power from PV systems only contributes a limited energy reduction, as it is shown in **Error! Reference source not found.**. Thus, it is easonable to avoid upgrading power infrastructure by limiting the maximum feed-in power from PV systems. This may be included in the future grid demands at a very high penetration level. The same philosophy may be imposed on other renewables (e.g. fuel-cell system). In that case, the control of power electronics should be ready.

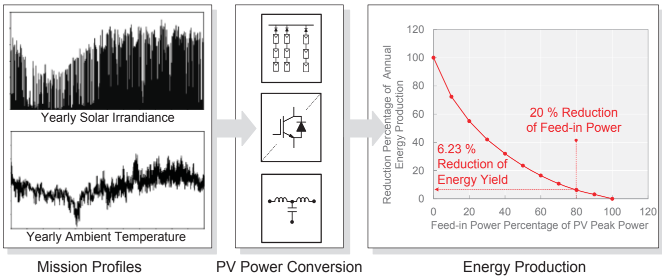


Fig. 20. Energy reduction due to the limitation of maximum feed-in power.

C. *Lower Cost of Energy*

Reducing the cost of energy is one of the most important considerations, in order to set a higher penetration of the installed capacity. Generally, a Levelized Cost of Energy (LCOE) index is adopted to quantify and compare the cost for different renewables [50]-[52], and it can be expressed as:

$$LCOE = \frac{C_{Dev} + C_{Cap} + C_{O\&M}}{E_{Annual}} \tag{1}$$

in which C_{Dev} is the initial development cost, C_{cap} represents the capital cost, $C_{O\&M}$ denotes the cost for operation and maintenance, and E_{Annual} is the average annual energy production in the whole lifetime. It is shown in (1) that the possibilities to lower the cost of energy are: a) to reduce the cost for development, capital, operation and maintenance and b) to extend the energy production or increase the lifetime of the generation system.

As it is shown in **Error! Reference source not found.**, the nshore wind power technology is currently competitive with the fossil-based power generation in terms of the cost, while offshore wind power and solar PV technologies are still more expensive than the onshore wind power. The cost advantage is the main contribution to the significant adoption of onshore wind power systems in the past few decades. As it is indicated in **Error! Reference source not found.**, there is large potential o reduce the cost of offshore wind and solar PV technologies in the future. Since the power electronics technology is the key technology for RESs with higher power ratings, special cost considerations should also be taken into account for the design and control of power electronics converters.

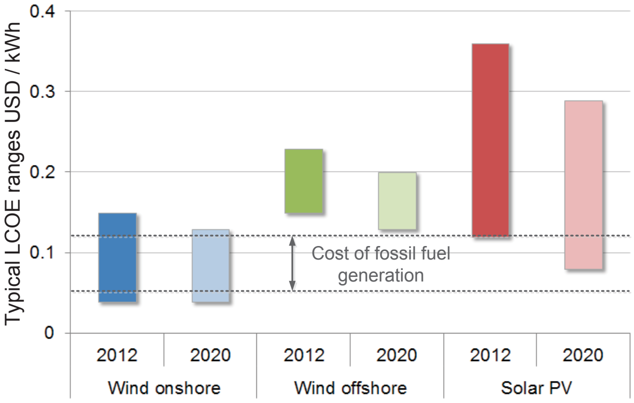


Fig. 22. Estimated LCOE for several renewable energy technologies for entering service in 2018 [51].

D. *High Efficiency and High Reliability*

Achieving high efficiency and high reliability are always of intense interest in order to reduce energy losses and to extend service time, and it will be further strengthened in the future RESs. Improvements of efficiency can be achieved by integrating more power electronics systems with intelligent control strategies and developing more advanced power electronics devices (e.g. SiC-based modules). For example, transformerless PV inverters will be even more widely adopted since they can achieve high efficiency. As the devices and components that comprise the power electronics system in a RES, the behavior of the power electronics devices will impose constraints on the system conversion performance [47]-[49]. Thus, for the future wind power systems with high power ratings, using advanced power electronics devices can improve the whole performance in terms of efficiency and reliability.

Notably, the dramatic growth of total installations and the individual capacity make the failures of wind power or PV system costly or even unacceptable. In view of this, the reliability is another critical requirement for the future RESs [9], [10], [14], [47]. According to previous research and field experiences, the control and power electronics systems in a RES have higher failure rate than the other subsystems. Therefore, possible improvements of the reliability can be achieved by means of: a) proper component selection (e.g. considering rated power, the most stressed situations, and the

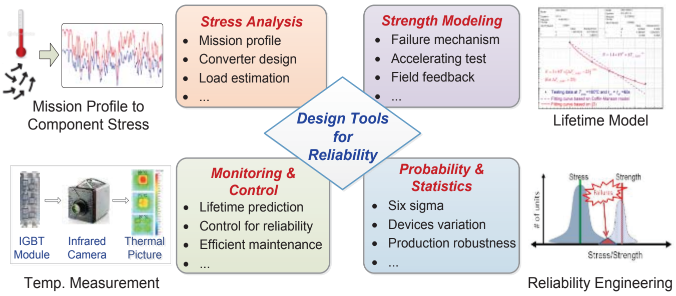


Fig. 21. Multi-disciplinary approaches for more reliable power electronics in renewable energy systems.

severe users, using advanced device packaging technologies, and choosing new power electronics devices), b) effective thermal management, c) robustness design and validation with the knowledge of mission profiles [9], [10], [47], [51]. These considerations should be taken into account during the design and operation of a RES. It also leads to possible activities for reliability analysis and improvement**Error! Reference source ot found.**.

E. More focus on thermal loading of power devices

According to the statistics carried by [59], the proportion of various stresses that contribute to the failures of power electronic components is shown in Fig. 23. It can be seen that 55% of the component failures are caused by the temperature or thermal stresses. It is noted that the stress distribution in Fig. 23 could be varied depending on the application, however as reported in [60]-[63] it is generally accepted that the thermal loading is an important “trouble maker” for most of the failure mechanisms in the electronic devices, like capacitor, printed circuit board, power semiconductors, etc.

It is proven that the thermal stress of the power electronics components can be mathematically translated into corresponding lifetime of devices, as summarized in [64]-[66], where a series of lifetime models are introduced. Fig. 24 shows an example of the lifetime testing results provided by Semikron, in which several fitting curves are plotted to represent the relationship between the thermal cycles to failure of a series of IGBT modules and the applied thermal stresses – in this case the junction temperature excursion ΔT_j and the mean junction temperature T_{jm}.

Based on the lifetime results tested by manufacturers, it is also possible to translate the complicated mission profiles of wind turbine and PV converter to the corresponding lifetime of power semiconductor devices, as detailed in [67], [68]. Moreover a new area of research can be opened which targets to smooth the thermal fluctuation of power devices and thereby improve the lifetime of power electronics converter.

An example is detailed in [69], in which it was found that the fluctuation/gust of wind speed or solar radiation could cause serious junction temperature fluctuation in the power devices – thereby compromising the reliability performance. A thermal controlling method is proposed in [69], in which the basic idea is to circulate the reactive power among paralleled converters to somehow stabilize the temperature fluctuation, as shown in Fig. 25. It can be seen that by enabling the reactive power control, the temperature fluctuation of power device caused by wind gust can be significantly smoothen – leading to improved reliability according to Fig. 24.

Another temperature control method is proposed in [70], [71], in which it was found that the junction temperature of some power devices in the wind power converter could be overloaded under grid faults. The basic idea is trying to change the thermal loading of power devices by utilizing the switching state redundancy in the three-level NPC inverter. The results are shown in Fig. 26, it can be seen that by enabling the new modulation method the thermal stressed of 3L-NPC converter under grid faults can be relieved and more balanced.

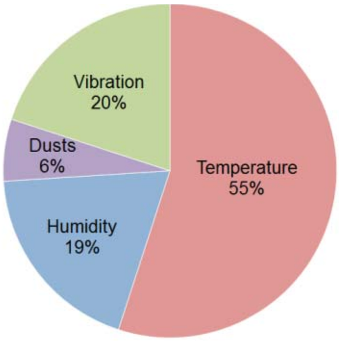


Fig. 23. Critical stresses contribute to the failures of power electronic components.

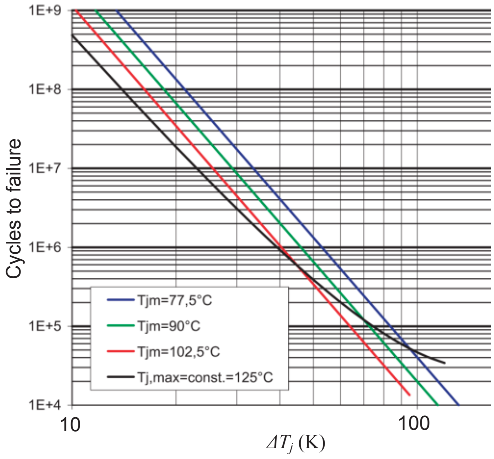
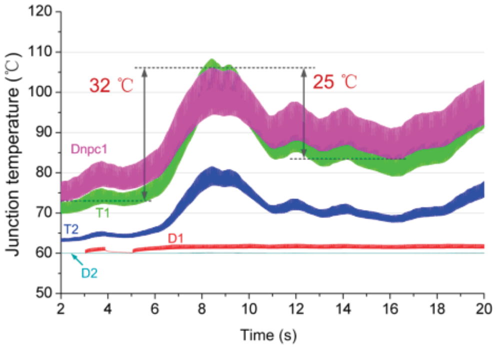
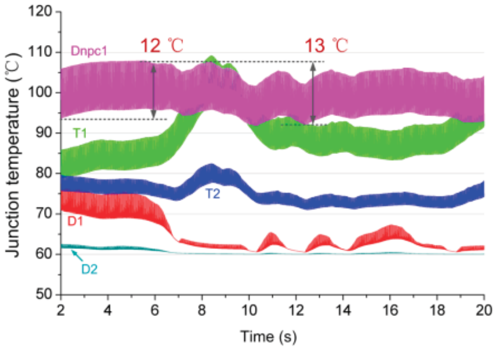


Fig. 24. Illustration of industrial standard cycles to failure vs. dTj of IGBT module by Semikron [65].

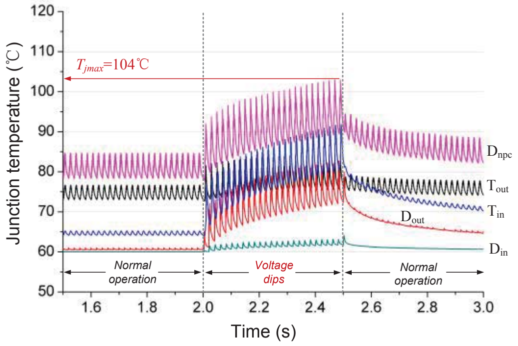


(a) without thermal control

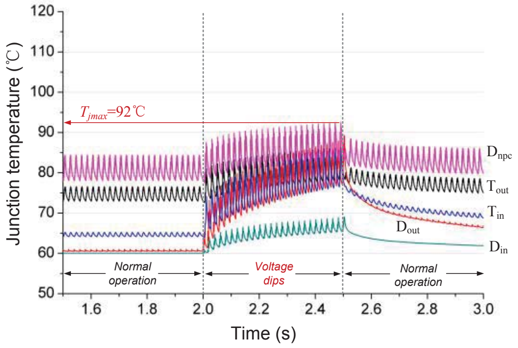


(a) with thermal control

Fig. 25. Thermal distribution of 3L-NPC inverter under wind gust operation [69].



(a) with normal modulation method



(a) with thermal optimized modulation method

Fig. 26. Thermal distribution of 3L-NPC inverter under grid faults operation [70].

VI. CONCLUSIONS

In this paper, the status and trends of the key technology for renewable energy systems – power electronics have been discussed. An overview of the technology demands and power converter topologies for kW residential PV panels as well as MW wind turbines are also given, together with the basic operation principles and control structures. Finally some emerging trends for the power electronics development in the renewable energy application are also discussed.

It can be concluded that the power electronics is a critical technology in the renewable energy generation systems. In the future, in order to enable larger scale renewable energy generation and reduce the energy cost, more advanced power electronics systems associated with intelligent controls, higher efficiency and reliability will be demanded.

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