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The Role of Power Electronics in Modern Energy System Integration

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Abstract: This paper will discuss different aspects of power electronics in modern energy systems. The transition from conventional, centralized power systems with large-scale generations to modern, deregulated systems with distributed generations is discussed. Furthermore, the function of some dominant green energy generation technologies based on power electronics is explained. Moreover, fundamentals of control and operation of modern systems with power electronics-based generations are presented in this paper. The major technical challenges that are deteriorating the overall system performance and reliability are addressed and feasible solutions are explained.

Keywords: Power system, energy system, power electronics, power converter, energy conversion, reliability, stability, energy storage, power-to-x, power to gas, control, planning, operation.

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1 Introduction

Decarbonization is the key to move toward climate neutrality and electrification plays a dominant role in making a greener society [1]. The modern society is becoming more and more interdependent on the electricity. Interconnections among various sectors, e.g., heating/cooling, transportation, water supplies, traffic controls are doable with electric power. This curtails/ eliminates the carbon footprint in different sectors. Furthermore, the supply chain of electricity from generation down to distribution needs also to be greener. This has been started with renewable generations many years ago to produce clean energy instead of using carbon-based fuels. Today, the renewable technologies are quite mature and the contribution of green energy generation is remarkable as shown in Fig. 1.

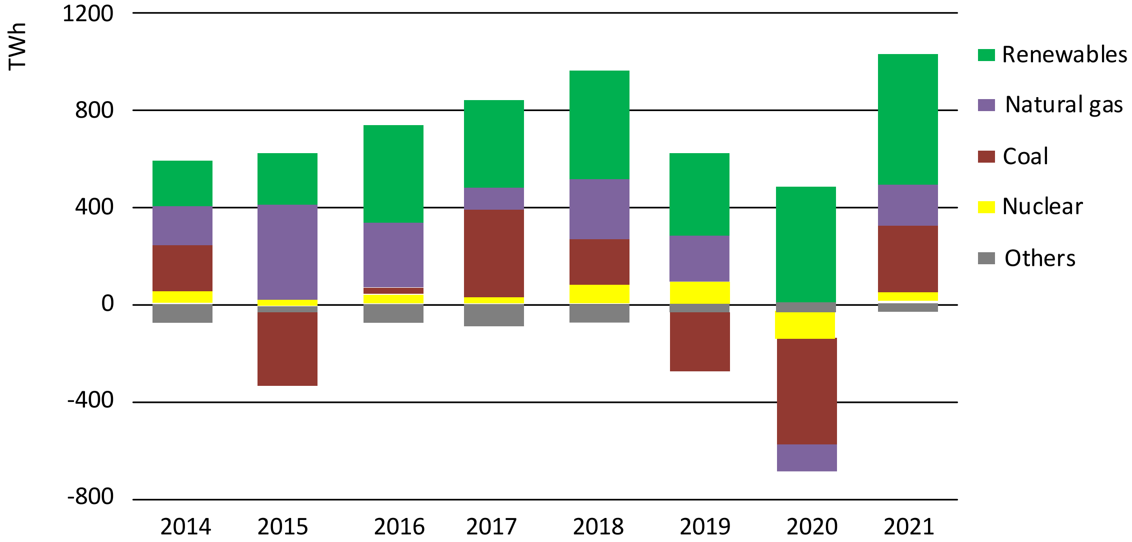


Fig. 1. Change in global energy generation, 2014-2021 [1].

Technically, moving toward renewable generations needs fundamental changes in power system structures both in physical and control/operation domains. This is due to the facts that (1) the capacity of renewable generation units is very small compared to the traditional power plants, and (2) they are integrated and controlled with power electronic converters. These factors induce major technical challenges to the more or full green power systems. Less flexibility in power control, lower inertia, fast response, needs for communications are some of major issues introduced by renewable generations. These challenges can affect the system reliability and performance, thus, introducing socio-economic issues. As a latest example, the Texas 2021 power crises in the state of Texas affected more than 4.5 million homes and businesses due to the shortage of electricity, water, food and heat. The power cut was initiated with the frozen wind turbines and solar panels [2]. Another interesting example could be the 900-MW photovoltaic (PV) power outage in California in 2017 due to the misfunction of power converter control units, more specifically its phase lucked loop in measuring the frequency [3]. These examples show how the transition from reliable but non-clean energy sources to the un-reliable but green sources can affect the human life. Therefore, moving toward green energy technologies need to understand the basics and provide solutions to guarantee the energy security and prevent irrecoverable damages.

Looking from electricity supply chain perspective, the power electronics converters become one of the major components in different parts of power systems. They are used in, e.g., interconnecting renewable generations, transferring high power among various location electronic transmission systems, distributing energy using AC/DC medium voltage transmission systems, load point applications like electric vehicle (EV) chargers. Therefore, their performance can remarkable affect the whole power and energy system security. This paper aims to provide fundamentals of energy transition in power systems with the specific focus on power electronics. First, the power systems structure will be described. Then, the concepts of planning and operation are explained to understand the basics of power system reliability. Afterwards, the modern electrical energy conversion with wind and solar PV is discussed and the application of energy storage and power to X is presented. Next, the basic structures of power converters and their control and operation principals are explained. Moreover, the principals of reliability in power electronics and fundamentals of system reliability assessment are discussed. Finally, some technical challenges of modern green power systems with more power electronics are presented.

2 Structure of modern power systems

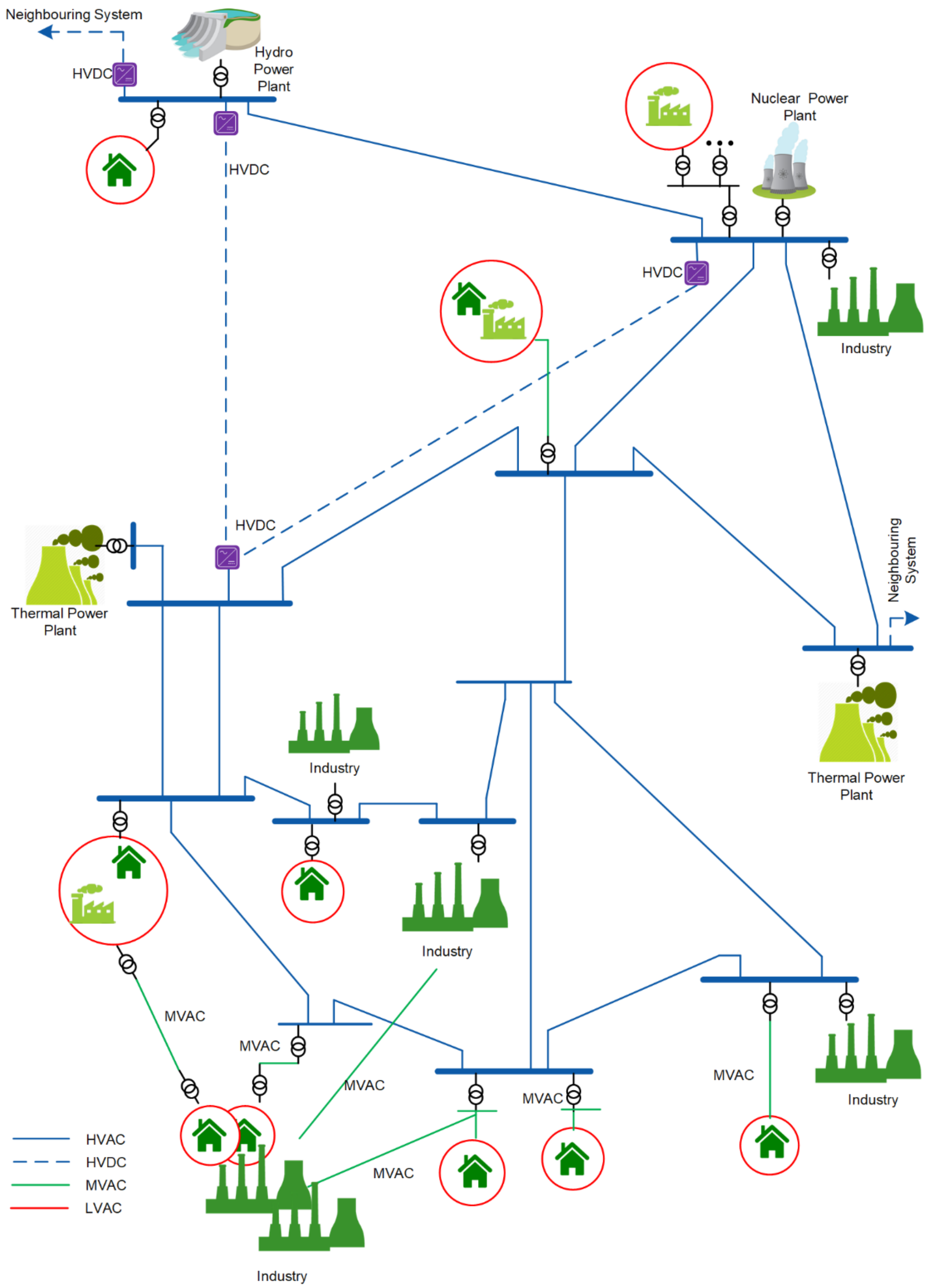


Fig. 2. Structure of traditional electric power grids.

In traditional electric power grids, electricity has been generated by thermal power plants, and delivered to the customers through high voltage transmission networks and medium/low distribution systems as shown in Fig. 2. Traditional power systems were controlled and monitored in a centralized way. Planning activities in traditional power systems such as marketing, energy management, unit commitment, monitoring and protection are performed by a central control and monitoring unit. Thus, adequate generation and transmission facilities are needed in order to supply the system demand that may require power transfer from one location to another with long geographical distance.

Environmental issues along with limited fossil fuel resources has highlighted the need for departing from fuel-based power plants to green energy generation systems. Therefore, small renewable-based generations such as wind and PV units have been incorporated to the power distribution systems [4]. Proliferation of renewable-based generation systems has initiated deregulation in electric power systems with new energy market players. The concept of distribution generations has gained more and more attention in order to develop the electric power grid structures. Also, the renewable-based power plants especially wind and PV systems have been integrated into the bulk power systems. Integrating distributed generations into the power distribution systems has initiated forming active networks, by energizing the distribution levels.

Furthermore, increasing use of renewable-based energy generation units with climate dependent output power needs using energy storage systems for eliminating the fluctuations of voltage and power as well as compensating the load generation imbalances. Also, using large-scale energy storage units are required in the full renewable energy-based power grids. In addition to the renewable generations, the modern technologies such as electronic transmission networks and e-mobility are key components of the smart and modern energy systems. The e-mobility especially passenger electric vehicles is growing rapidly, and it is integrated into distribution systems which will affect the long- and short-term planning as well as operation of the electric power grids. Furthermore, fast charging stations may require proper infrastructures and adequate power to supply the batteries in a desired time. For public transportation such as electric trucks and busses, wireless charging stations can enhance the serviceability of the transportation services. Moreover, intelligent and smart control and operation strategies are required for efficient and reliable operation of the electric power systems with increasing uptake of electric vehicles.

The electronic transmission networks including high and medium voltage systems are also facilitating the modernization of power systems. Mowing towards full renewable-based energy systems has imposed inter-connection of electric power systems, that could be done by using High Voltage DC (HVDC) transmission networks. Furthermore, the future distribution networks will be energized by renewable-based units, energy storages and EVs to supply the local demand. Secure operation of such complex systems could be doable by inter-connection of the medium voltage DC and AC distribution networks. Electronic transmission networks at the medium voltage level, i.e., MVDC systems, can integrated AC and DC grids [5]. This will have more advantages over AC grids in terms of cost-efficiency, energy-efficiency and reliability.

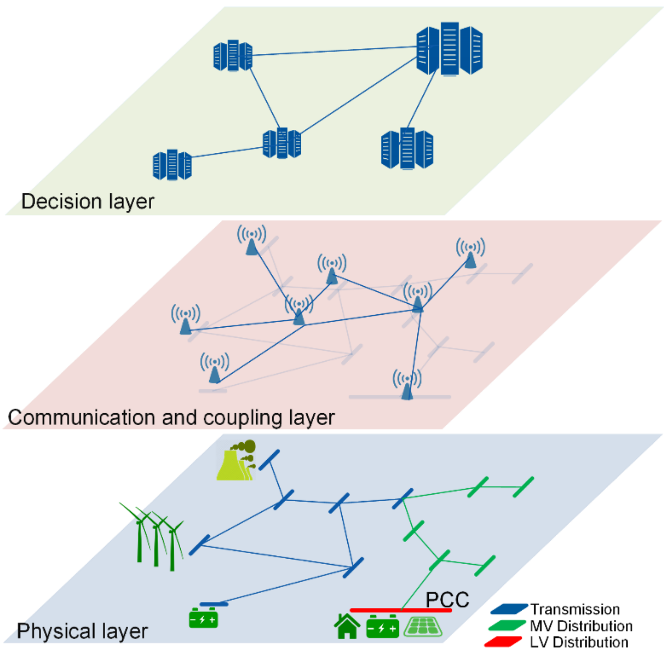


Fig. 3. Cyber-physical structure of modern electric energy systems.

In order to optimally and reliably new technologies such as green generations, energy storage, microgrid mode operation and EVs, smart control systems and real-time monitoring is required. Control and monitoring can be performed decentralized or distributed. As a result, future electric power systems will be made up of cyber and physical layers with the help of information and communication technologies. Fig. 3 shows different layers of modern power systems [6]. Integration of more and more new technologies, will change the structure of power systems to be a hybrid AC-DC grids in transmission and distribution levels as shown in Fig. 4. In comparison with the traditional electric networks, the renewable-based power plants and large capacity energy storage units are integrated into the transmission network. Also, medium voltage distribution networks are interconnected thought MVDC transmission systems.

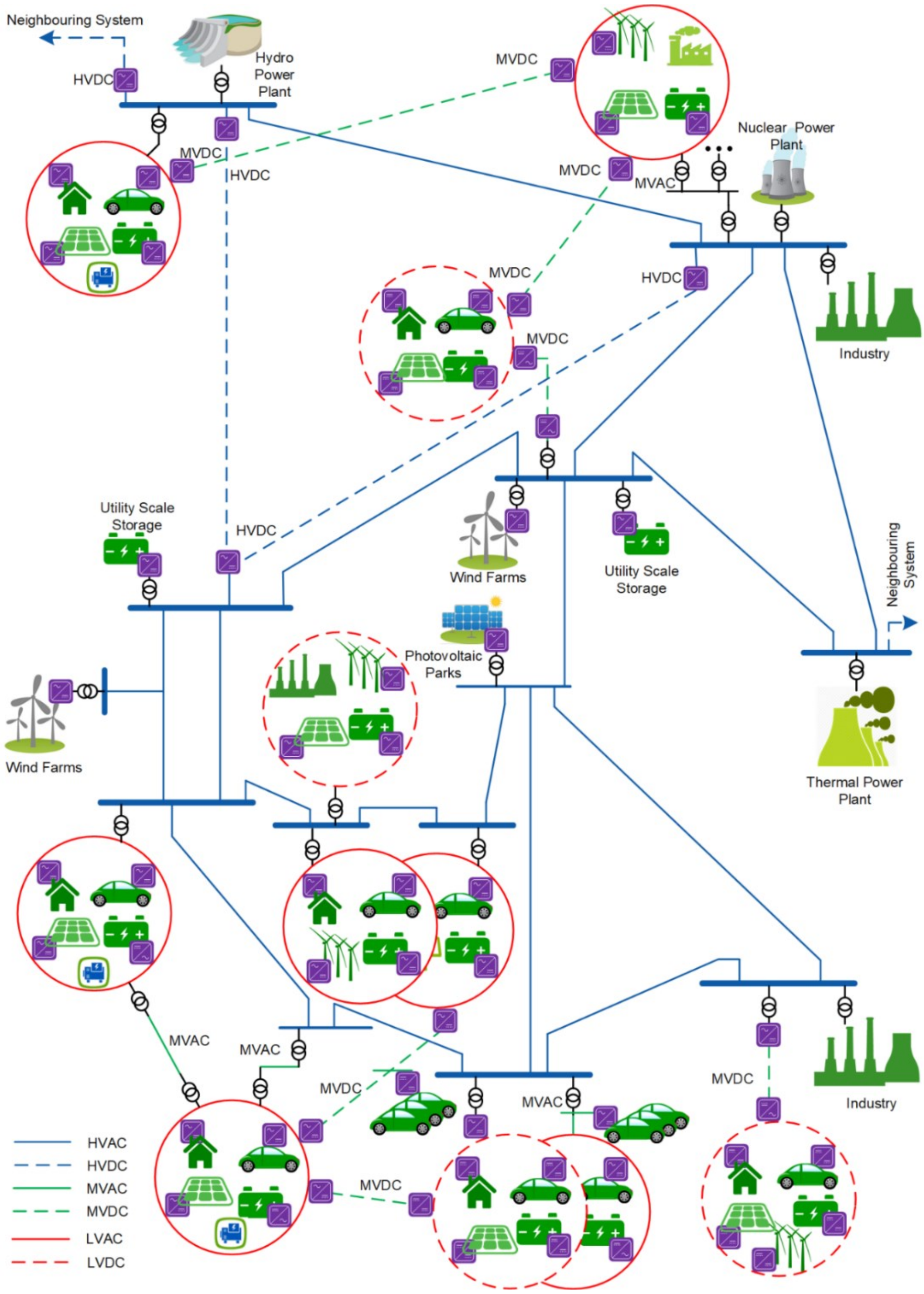


Fig. 4. Structure of power electronic dominated power systems with hybrid DC and AC grids.

Energizing the distribution power grids and operating them in the microgrid mode as active networks will introduce some major advantages such as high reliability and availability, and better efficiency [7]. This is due to the fact that the microgrid technology facilitates the distribution systems to be operable in terms of any unpredictable contingency and outage events, that may disrupt energy delivery to the customers. A microgrid is defined as an active electric network with adequate energy sources mainly based on renewable energies and also energy storage to feed its critical demand in both grid connected and islanded modes [8], [9]. Therefore, interconnected hybrid AC/DC grids will be the structure of modern distribution power networks as shown in Fig. 5 [10], [11].

The microgrid topology can be categorized based on the structure of distribution grid. Considering the location of protection devices and protection approaches in the distribution network, it can be divided into a single-customer, partial-feeder, full-feeder and substation microgrids as it is shown in Fig. 5 [11]. Furthermore, according to the rated power of a microgrid, it can be divided into pico-grid, nano-grid, micro-grid, milli-grid and inter-grid [10]. Technically, the distribution grids considering the energy units and protection systems design needs to be coordinated where any islanded sub-grid can independently be operable [10]. The microgrids can be DC, AC or hybrid AC/DC networks [12] depending on the types of energy source and loads.

Operation of future distribution grids with complex structure of generations, storage units and control/protection system in a centralized way needs information and communication networks that is, in practice, not an efficient, cost-effective and stable solution. Therefore, distributed and/or decentralized energy management approaches with local communication systems can facilitate optimized and reliable operation of distribution networks as smart grids [13]–[15]. Thus, both control and structure of future distribution systems will be as distributed as possible both in structure and control levels. Moving toward distributed structure, the overall system efficiency, reliability and stability will be enhanced. Moreover, having control and operation systems in a distributed way enhances the system resilience against high impact events such as large disturbances and cyber-attacks.

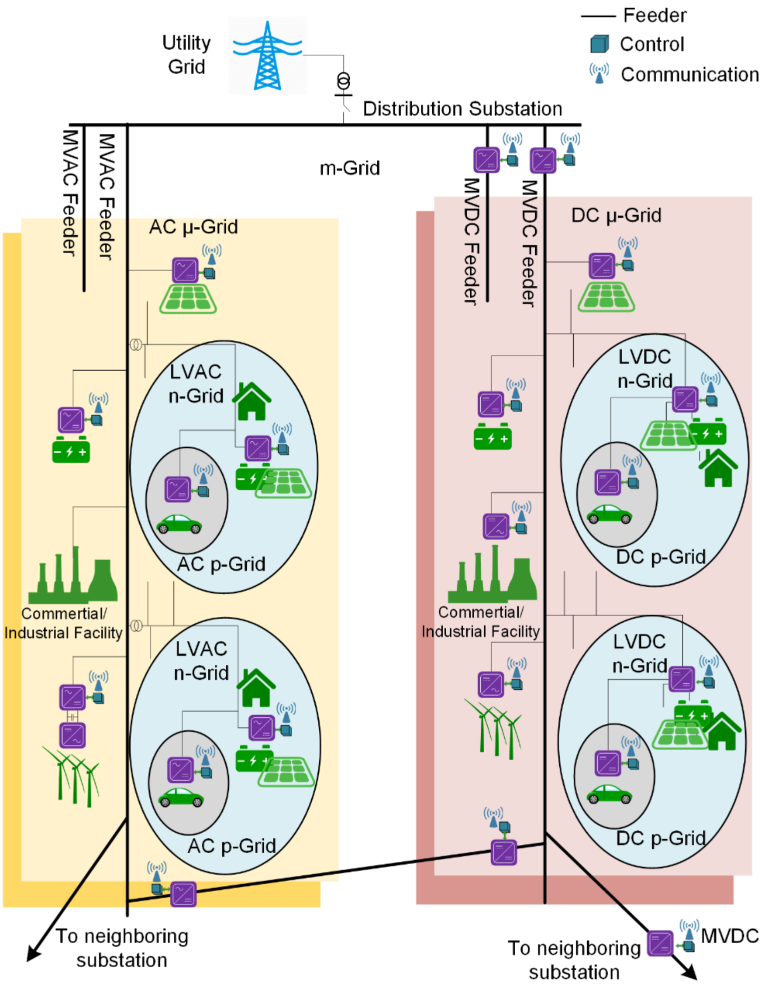


Fig. 5. Multi terminal hybrid DC and AC distribution power grids –m-Grid: Milli-grid, p-Grid: Pico-grid, n-Grid: Nano-grid, μ-Grid: Microgrid.

2.1 Power System Engineering

Power system engineering is mainly dedicated to planning and operation. It is a set of processes to design, expand, monitor, control, and manage, the electrical networks in order to optimally, economically and reliably supply end-consumers. It needs various studies and analysis in different phases from micro-seconds to even several years. Electric power system analysis can be performed in three phases including facility planning, operational planning and real-time operation as shown in Fig. 6.

Power system planning is classified into two classes; facility planning and the operational planning [16]. Facility planning aims to install and expand the power networks over 5 to 30 years, while the operational planning is to plan for the existing facilities in a few minutes to 1 year [17]. The main objective in facility planning is to expand and develop power networks facilities such as addition of power generation systems, expansion and reinforcement of distribution and transmission networks considering technology development and load growth. Moreover, operational planning is subjected to optimal and cost-effective employment of the existing generations, transmission and distribution facilities to supply the present demand at the real time. Furthermore, power system operation is in charge of continuously monitoring, control and operating of facilities in order to economically sustain the normal operating state. The main aim of power system operation is to ensure a desired reliability performance with respect to operational costs in supplying customers.

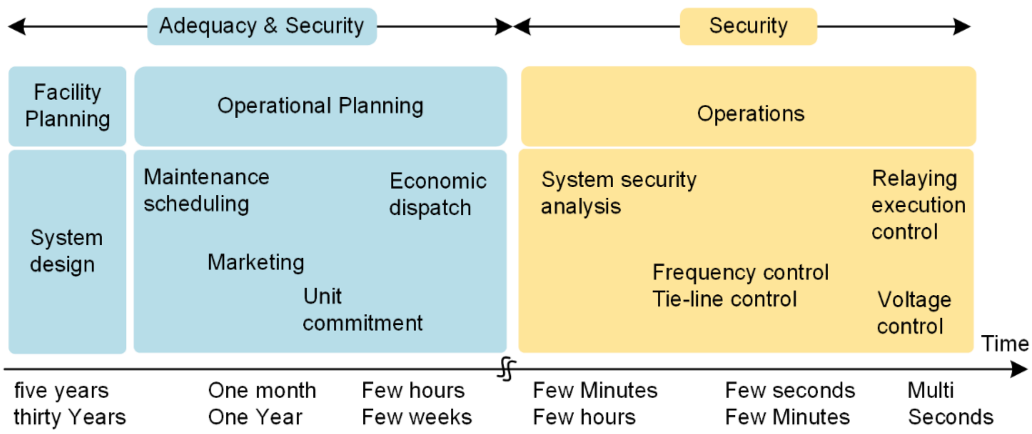


Fig. 6. Power system engineering concepts.

Conceptually, the reliability of electric power systems is defined as its ability both in cyber and physical layers to support the grid demand with a specified level of performance [18]. It is categorized into two main concepts of adequacy and security. The first one is associated with the existence of sufficient facilities in generation and transmission levels to support the consumers considering intended and unintended contingencies. Also, security is subjected to the ability of an electric power system to respond to any planned and unplanned disturbances arising within the system. Conceptually, adequacy is related to the power system planning and security is related to the real-time operation. However, in the planning phase the security is also considered to ensure a desired level of reliability subjected to credible outages. Different time scales of planning and operation in electric power engineering is shown in Fig. 6.

A. Planning

Facility planning considers the emerging technologies, technology development and load growth and to install new equipment and expand power girds in the upcoming 5 to 30 years [17]. The main aim of this planning is to guarantee having sufficient capacity by on-time and economic expansion of power networks.

Operational planning is related to the electricity marketing and maintenance planning. Conceptually, power system maintenance can be performed in two ways either corrective or preventive, or both. In the preventive maintenance, the system repair and replacement are timely done to reduce a failure occurrence, while corrective maintenance is outperformed after a failure occurrence to restore the system to the operating condition. As a result, maintenance planning can remarkably impact the availability of power system and corresponding operational costs.

Moreover, power system operational planning aims to schedule the existing generation units to supply the grid demand in the next hour, next day, next week, next season and next year. This requires to look at several electricity markets with different purposes. The energy is traded by different market players for a fixed period in the coming day in other to economically support the customers. In the hour of delivery which is related to intra-day market, the grid demand and generation status are much clear compared to the day-ahead marked. Thus, the market players can re-plan according to the curtain grid conditions. Moreover, spot markets, i.e., the day-ahead and intra-day markets indicate short time between planning and power delivery. The previous markets face load forecasting uncertainties, thus the imbalance between estimated and actual load power needs to be traded in the balancing market by the balance responsible players, i.e., the generators participating in frequency control. The droop controllers known as primary reserve is in charge of immediately supporting the demand-generation imbalance by the primary frequency droop control of generators. Also, the generators participating in the secondary and tertiary reserves will support generation-load balancing market by trading in balancing market within several minutes. Moreover, after real power delivery the power mismatches will financially be settled in post-delivery market.

In the deregulated and liberalized market environment, the Independent System Operator (ISO) is in charge of interconnecting the energy producers, i.e., power plant owners to the retailers and consumers to figure out an optimal scheduling of the generation systems and transmission networks. Thus, to optimize the profits, unit commitment among different players is performed. Unit commitment defines the generated power of the set of generators to be on/off/standby during a planned time, based on the predicted load and electric power grid present conditions. The unit commitment will be re-scheduled hour by hour in order to maximize the profit considering the operational costs, emission costs and so on.

B. Control and operation

The TSO has been responsible for marketing, maintenance planning, unit commitment and economic dispatch for optimally scheduling the power generators in the operational planning phase. The next step is the real-time operation, in which, the power plants have been scheduled to generate the pre-defined powers, primary reserve providers compensate the load-generation mismatch and then the secondary and tertiary reserves, i.e., spinning reserve suppliers deliver the load-generation imbalances induced by load and renewable generation forecast uncertainties, and unintended outages. These concepts are subjected to the power system adequacy. Also, in the real-time operation, the main concern of operators is the system security; it is of high importance to how secure the power system is in its running condition and how secure it is going to be in the upcoming several minutes [19] subjected to unpredictable contingencies. Hence, the system security becomes the important issue during real-time operation.

Therefore, the security is thus related to its ability, both at facility and control, to withstand to any planned and unplanned contingencies and disturbances in the power system [19], [20]. A secure power system is able to sustain its stability, and retain its voltages and thermal limits in an acceptable value in the case of any unpredicted events. It is performed online using dynamic security assessment tools.

At the real operation time, the system operator should know the present and running state of the power system. The system present state, which is the power grid structure, generation of power plants, loading of lines, voltage of busses, should be monitored by Supervisory Control And Data Acquisition (SCADA) system, Phasor Measurement Units (PMUs) and Remote Terminal Units (RTUs), that require information and communication infrastructures [16]. Having these infrastructures are necessary for the sake of control and monitoring such a complicated system. Moreover, the missed data can be predicted using a state estimation process. The collected data are used by state estimation block to find out the current operating status of the power grid by estimating the grid parameters that are not available for the monitoring system.

Afterwards, the power system operator should perform contingency analysis based on the present state of the power network to figure out the consequences of the any likely contingencies and outages on the operational performance of power system in order to ensure a certain security level for the next upcoming few minutes. Therefore, the operator needs to check the dynamic/transient security as well as the static performance in the presence of any unpredictable events. The static security is attributed to the ability of power system to sustain the voltage and thermal limits of different components including power lines, converters, transformers in steady state. This is performed by running power flow and optimal power flow programs conceding all credible contingencies to check the violation of the voltages and thermal limits. Moreover, the system operator needs to check the system ability for any credible disturbances to get ready to sustain the system stability in the case of contingency occurrence. According to the instability causes, the stability issues are traditionally classified into four categories of voltage stability, frequency stability, angular stability and converter driven stability.

The protection system must be properly set and coordinated with the other devices to react in a suitable time to protect the faulty zone and /or equipment. After analyzing the security of a power system and understanding the fragile points of grid subjected to some disturbances and contingencies, the system operator needs to take proper actions either corrective and/or preventive to sustain the overall system security. These remedial actions can be re-planning the dispatchable generators, splitting the power network into several islands, load shedding and so on. The islanded areas or shutdown systems need to be restored on-time by the operators.

3 Electrical energy conversion

In this section, the basics of energy generation systems in traditional and modern power systems are explained. Notably, there are various types of energy generations with diverse prime movers, conversion technologies, etc. The traditional ones can be classified as hydropower, nuclear power plants, and thermal power plants. The modern generations systems are renewable energies (wind, solar photovoltaic, solar thermal, geothermal, …), storages, and power to X (Gas, …). In the traditional ones, Coal-based thermal power plants are dominantly used in power systems. Moreover, among the renewable energies, wind and photovoltaic are widely adopted in power systems. Therefore, this paper is going to focus on the dominant power generations systems. First, the main concept of energy conversion is presented. Afterwards, the renewable based energy generations including wind and PV power plants are discussed. Moreover, the concepts of energy storage and power to X are introduced.

3.1 Thermal power plants

Electric power is conventionally generated by thermal power plants. For many years, thermal power plants have been the main energy generations, converting the energy of fusil fuels to electricity. The schematic of the whole process of electricity generation is shown in Fig. 7. The fuel energy is used to heat a gas or fluid, depending on the power plant thermal cycle, in a boiler. The hot fluid is injected into a turbine, or series of turbines, to convert its energy to rotational energy. The turbine is mechanically coupled with a generator. In the generator, the rotational energy is converter to the electrical energy. In order to run the thermal cycle, the fluid is cooled down by a condenser. Therefore, the thermal power plants convert the chemical energy of fuel to the electrical energy in several steps. Mainly, there are two thermodynamic cycles in power plants; Rankine cycle used in steam turbines and Brayton cycle used in gas turbines.

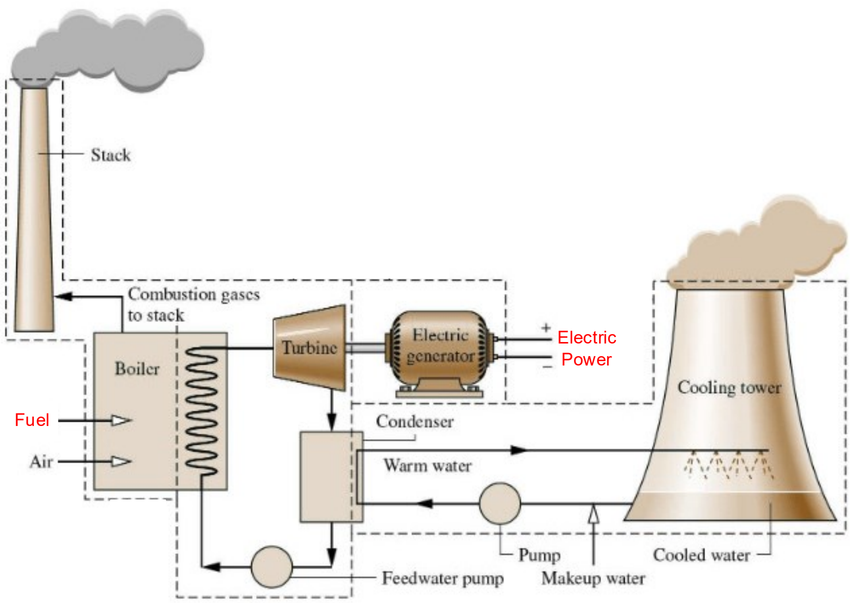


Fig. 7. Basic structure of thermal power plants.

The basic operation principals of the electric generators rely on the Faraday's Law. Based on Faraday's law, the electro-motive force induced in a loop is proportional to the rate of change of magnetic flux through that loop. According to Fig. 8, there is a fixed magnetic field from N to S. The yellow loop is rotating with the speed of ω. Therefore, the magnetic flux cutting the surface of the loop is changing the rotational speed of ω. This will induce electro motive force in the loop and if it is connected to the load, electric current will be induced. This is the fundamental of electric generators. In Fig. 9, the basic structure of an alternative current (AC) generator is shown. In this structure, the windings are fixed on the frame, so-called stator. The magnet is located in the center of frame which is can be rotated by a prime mover like a steam turbine. Therefore, the flux cutting the windings are changed with the rotational frequency of the magnet. Therefore, electro move force is induced in the windings. Connecting these windings to the electric loads will induce current and supply their energy.

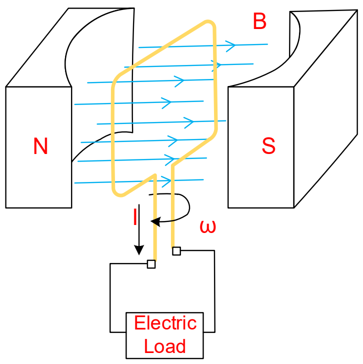


Fig. 8. Principals of Faraday's law.

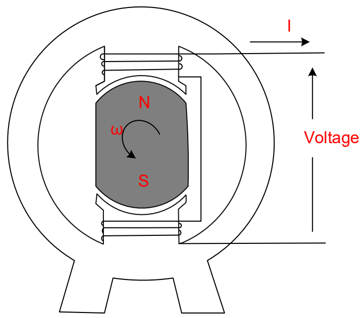


Fig. 9. Basic structure of AC generators.

3.2 Wind Power Generation Technology

The prime mover in traditional power systems was turbines fed by fusil fuels. Today, remarkable part of electric energy is supported by the wind energy where the wind turbines are work as the prime mover for generators. For converting the wind energy to the electric power, there are several different generators and power electronic converters to accomplish this goal. Following the power electronic converter capacity, it can generally be classified into two types: partial-scale power converter and full-scale power converter.

The first wind power generation structure is shown in Fig. 10, which is based on the Doubly-Fed Induction Generator (DFIG) and only uses a power converter with the rated power of approximately 30% of the nominal wind turbine power. The power converter is connected to the rotor windings to controls the rotor current and rotor speed, and the stator is directly connected to the power grid. The fraction of slip power by the converter makes this concept interesting from an economic perspective. However, the main drawbacks lie in the use of slip rings, and also an additional crowbar might be required to protect the rotor-side converter under grid faults [21], [22].

As shown in Fig. 11, a full-scale power converter structure is considered a promising solution for a multi-MW wind turbine system. The stator windings of permanent magnet synchronous generator (PMSG) and/or induction generator (IG) are connected to the grid using a full-scale power converter, which provides a reactive power compensation and a better grid connection for the wide speed range of the generator. Some variable speed wind turbine systems are gearless by employing a multi-pole generator. The elimination of the slip rings, a simpler gearbox and full power controllability during the grid faults are the main advantages of such structures [21]–[24]. However, several parallel converter modules or power devices should be employed in order to support the full power rating.

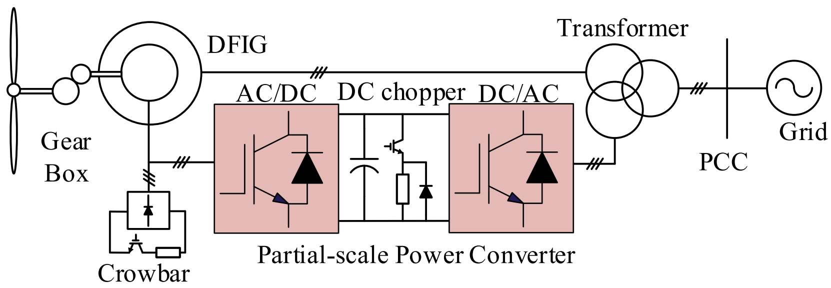


Fig. 10. Wind system using partial-scale power converter (DFIG: Doubly fed induction generator).

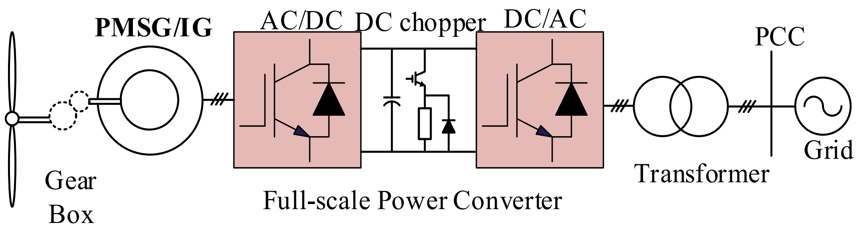


Fig. 11. Wind system using full-scale power converter (IG: induction generator, PMSG: permanent magnet synchronous generator).

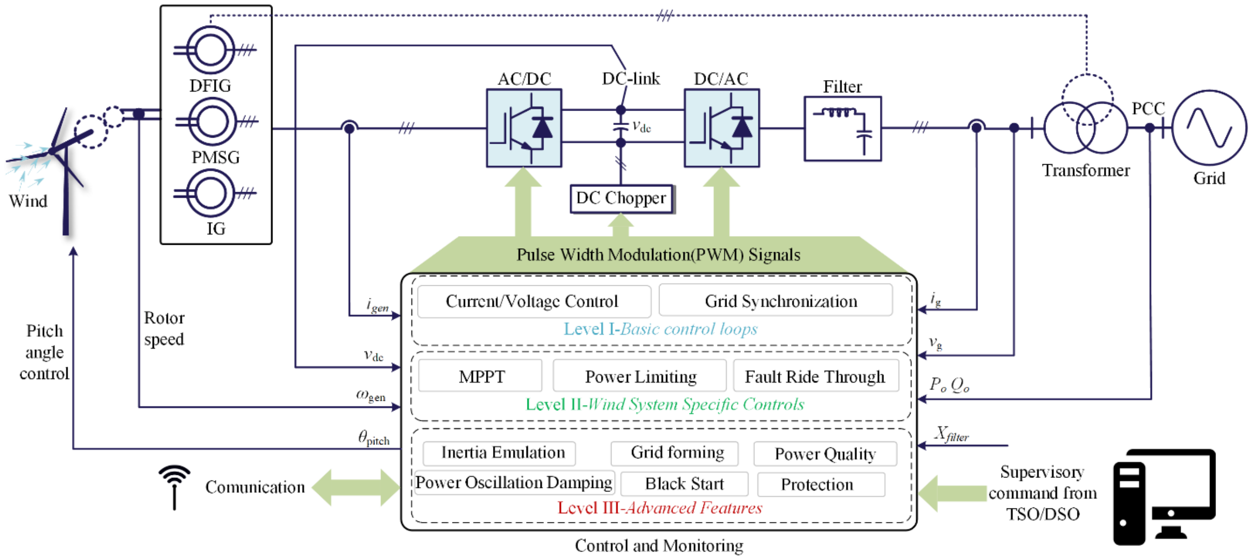


Fig. 12. Control structure for wind systems (v_{dc}: dc-link voltage, i_{gen}: generator current, θ_{pitch}: pitch angle of rotor blade, ω_{gen}: rotational speed of generator, X_{filter}: filter impedance, i_g: grid current, v_g: grid voltage).

As it can be seen in Fig. 10 and Fig. 11, a wind turbine control system involves both fast and slow dynamic controllers, since both the mechanical and electrical conversion sub-systems need to be controlled. The control functions can be classified into three levels: Level I: basic control loops, Level II: wind system specific controls and Level III: advanced features, as shown in Fig. 12 [4], [25].

At Level I, it is always the inner control loop with the fast dynamics and highest bandwidth. At this control level, the tracking of the active power and reactive power reference are realized by the control of the generator stator current and grid-side converter current. Furthermore, in order to decouple the generator-side converter and the grid-side converter, the dc-link voltage is required to be regulated at a constant value. For the traditional vector control, the grid synchronization, using, e.g., Phase-Lock Loop (PLL) technology, is implemented to provide accurate phase information.

At Level II control level is generally designed to attain the maximum electric power from the wind turbine at normal operation and limit the active power during the grid fault by the response of the mechanical part. Normally, with the help of the maximum power point tracker, the active power reference can be obtained by the generator speed. If the wind speed goes higher than the rated wind speed or the fault ride-through operation is enabled, the mechanical power is actively decreased by the pitch control.

Level III receives the commands from the transmission system operators (TSOs) and/or distributed system operators (DSOs) or wind farm operator, the entire wind generation system needs to satisfy these demands through the mechanical and electrical controllers. Since the integration of large-scale renewable generations into the grid, the inertia and strength of power grid are decreased, thus, more advanced functions should be implemented, such as the inertia emulation, grid forming, power quality enhancement, power oscillation damping, black start and so on [26]–[28]. Notably, various control functions can be achieved by the appropriate control system and adjustment of the entire wind turbine system. Hence, the resiliency of smart grids can also be improved by implementing appropriate control methods.

3.3 PV Power Generation Technology

Beside conventional generators and wind systems, there are other technologies that operate without mechanical rotating part including photovoltaic (PV) and full cell. The PV technology is considerably integrated into power system with large scale power plants. Thus, in this part, the PV system are presented. PV systems are working based on the photovoltaic effect. The principal of PV effect is shown in Fig. 13. Fundamentally, sunlight is composed of photons, which can be considered as discrete units of the energy stored in light. A PV cell is made up of semiconductor materials with a p-n junction. Once the solar radiation strikes a PV cell, part of the photons can be absorbed by the cell. This will result in the production of electron-hole pairs in the PV cell. If an external load is connected to the PV cell, the generated voltage will drive the electrons from the n-side to the p-side of the junction. Therefore, the electric current is formed and passes through the external load.

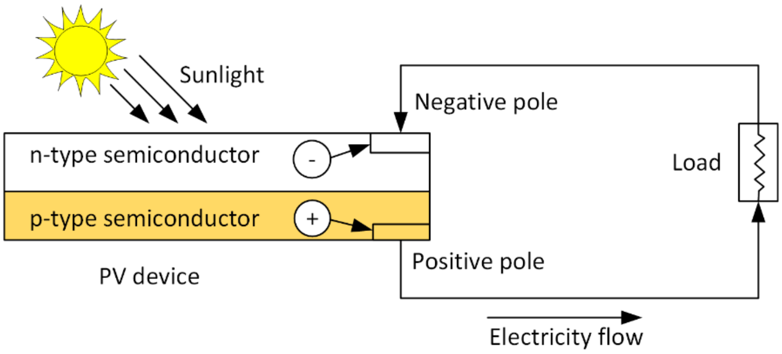


Fig. 13. Photovoltaic effect.

The PV cells modeling involves P-V (output power-output voltage) and I-V (output current-output voltage) characteristic curves. Most ideal PV cells have been modeled as a p-n junction with a Shockley-based equivalent circuit. Fig. 14 shows the basic PV model, which comprises of a diode and an ideal current source.

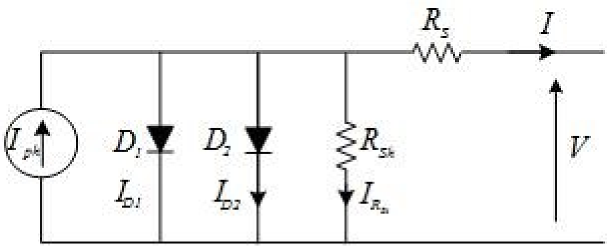


Fig. 14. Ideal model of a PV cell (I_{ph}: photo generated current, I_D: Diode current, I: PV cell current, V: PV voltage).

The mathematical description of the I-V characteristic of the PV model is:

$$I = I_{Ph} - I_D \qquad (1)$$

where I is the output current of the PV cell, I_{ph} is the photo-generated current by the sunlight that is proportional to the solar irradiance level, and I_D is the Shockley current modeling the diode behavior as:

$$I_D = I_0\left[e^{\frac{qV_D}{\alpha kT}} - 1\right]$$
$$I = I_{Ph} - I_{I_0}\left[e^{\frac{q(V_D+I)}{\alpha kT}} - 1\right] \tag{2}$$

where I is a reverse bias current of the diode, k is the Boltzmann's constant, q is the charge of an electron (= 1.602×10^{-19} C), and T refers to the absolute p–n junction temperature in Kelvin, and α is the diode ideality factor typically within 1 to 2 [29].

As the power of a single PV cell is very low, a great deal of PV cells should be connected in series and parallel to form a PV module/panel up to several hundred Watts. In a similar way, the PV modules/panels can be connected in series and parallel to further achieve high-power and high-voltage PV arrays. The number of series and parallel panels in each PV array is dependent on the P-V characteristics of each panel, the input voltage, and the rated current of the interfacing converter. Furthermore, as the output power of PV panels varies following the solar irradiance and ambient temperature, an interfacing converter is required to control the output current of the PV panels to harvest the maximum power. This is called a maximum power pointing tracking (MPPT) control.

With the fast development of PV cell technologies, the continuous cost reduction of PV modules, and advancements in power electronics, the PV power generation system has been widely deployed in modern power grids [30]–[33]. It is expected that the cost of PV technology will continue declining, which will make PV systems competitive among other renewable energy systems. Hence, more PV generation systems will be seen in the future.

Power electronics are the key component to transfer the solar energy to electricity effectively and reliably. Thus, it is of significant importance to investigate different topologies and control strategies for connecting the PV panels to the grid.

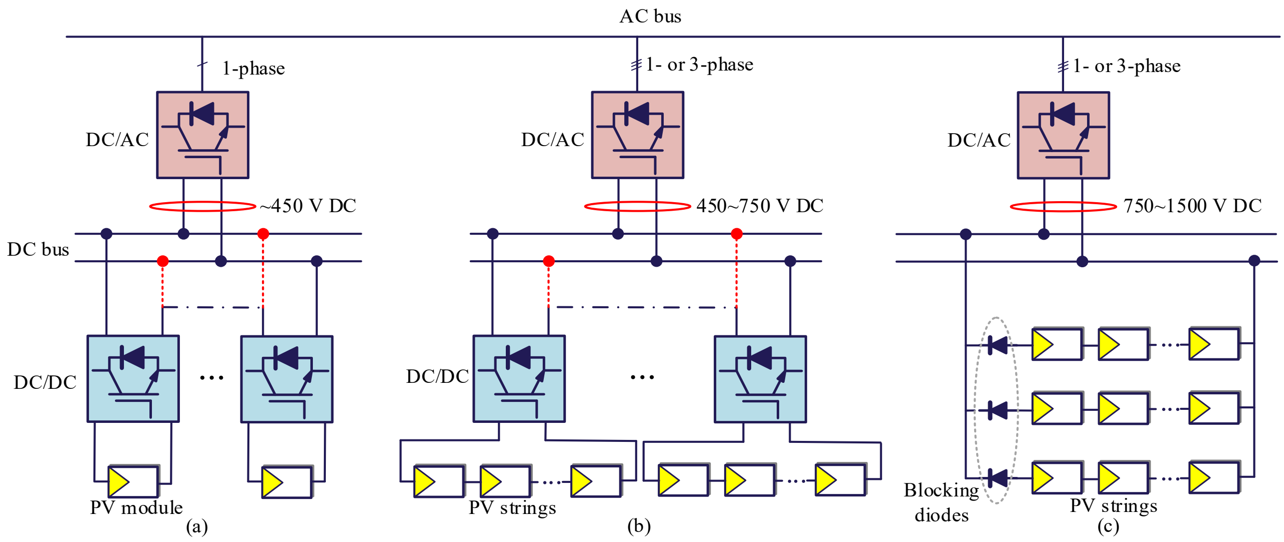


Fig. 15. Configuration of PV power systems: (a) PV module inverter for low-power applications; (b) string inverter for medium-power applications (c) central inverters for utility-scale systems.

The widely used topologies for connecting PVs to the AC grid is shown in Fig. 15. Unlike the wind power technology, the solar PV produces far less power per generating unit (e.g., a single PV panel or string). Thus, for single PV module, it is always connected to the ac bus through a DC/DC and DC/AC converter, shown in Fig. 15(a). In order to increase the output power within an acceptable range, many panels or strings are connected in parallel and/or series, as shown in Fig. 15(b) and (c). In these two cases, the string/multistring inverters and center inverters are adopted as the interface to the distributed grid. The central inverter technology is the most widely adopted alternative for distributed power grids, as it is the simplest way to collect DC power from PV panels with a low construction cost. Moreover, for a high-power and high-voltage PV generation system, multilevel power converters can be employed. In addition, several central inverters can be connected in parallel to increase the power-generation flexibility.

Although the variability of the PV inverter topologies and system configurations increases the control difficulty, the general control objectives for a PV generation system are universal, including MPPT, grid synchronization, voltage/current control, active power control, Anti-Islanding (AI) protection, system condition monitoring (e.g., PV panels), and ancillary services (especially for resilience enhancement), as summarized in Fig. 16. With the increasing PV capacity, the power flowing in and out of the PV generation system must be managed using other systems (e.g., energy storage systems) or even through itself; otherwise, the distributed grid voltage level and frequency may be violated. As previously mentioned, the entire wind generation system must follow the set-point commands given by the TSO/DSO for system stability concerns. This also applies for the PV generation system. That is, the more advanced features required for the wind generation system in the past are now considered for the PV generation system, as the power capacity is drastically increasing in many areas. For instance, delta power production control, frequency control through active power, voltage control through reactive power, the ride-through operation of the distributed grid faults, and the provision of grid support in both normal and abnormal conditions to the grid have been adopted [34], [35]. Typically, those features can be implemented in the control loops of the power converters. Regarding the fault ride-through operation, because the PV generation system has far lower physical inertia (no rotating components) than the wind generation system, the control is simpler. However, in this case, the excessive active power from PV generators should be dispatched by 1) modifying the MPPT control; 2) activating the DC chopper to absorb power; and 3) managing the power exchange between the PV panels and the extra energy-storage systems. Notably, in these cases, the basic functions, such as current regulation, DC-link voltage stabilization, grid synchronization, and anti-islanding protection, must be quickly performed. Regarding resilience enhancement, the high-level coordinative control and operation among various renewable energy generation systems may also be needed.

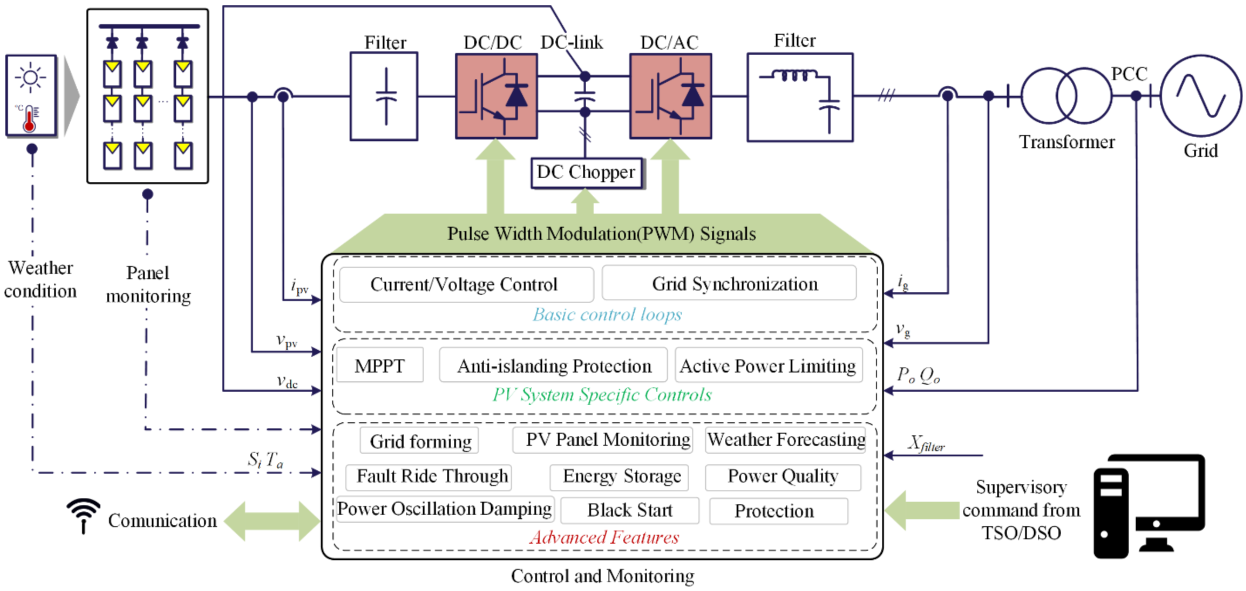


Fig. 16. Control structure of a PV system (v_{dc}: dc-link voltage, i_{pv}: PV current, v_{pv}: PV output voltage, T_a: ambient temperature, S_i: solar irradiance level, i_g: grid current, v_g: grid voltage, X_{filter}: filter impedance).

3.4 Energy storage system

Since the wind and solar are always stochastic and intermittent, it is essential to equip the wind and the solar with Energy Storage Systems (ESSs). ESSs can be regarded as special distributed energy resources (DERs) with four-quadrant operation capability. They can not only provide mobility and emergency power, but also help the grid to manage load profiles (peak-shaving and valley-filling), smooth renewable power, and provide fast ramping up and down power for ancillary services avoiding expensive spinning generators. In conclusion, ESS assists renewable energy integration in many ways and manages the decent power balance during a power crisis in the grid.

For deploying the energy storage system into the renewable energy integration, there are generally two connected types: aggregated configuration and distributed configuration. The aggregated ESS units serve the whole wind/PV farm through the AC bus. However, the distributed ESS units are installed in each WT/PV generator through the DC-link as shown in Fig. 12 and Fig. 16.

Fig. 17 (a) shows the aggregated ESS configuration, where the ESS is usually connected to the AC bus of the wind/PV farm. Since the output of the energy storage is always a DC source, a DC/AC converter interface is necessary to connect them with the ac system. Fig. 17 (b) shows the distributed ESS configuration, where ESS units are directly connected to the DC-link of each wind turbine/PV generator. For variable speed wind turbine generators, like the DFIG in Fig. 10 and PMSG/IG in Fig. 11, the DC ESS unit can be easily installed to the DC link. For the same ESS power rating, a DC/DC converter is simpler and cheaper than a DC/AC converter.

For the aggregated ESS unit connection, the grid-forming control strategy is usually adopted to the DC/AC inverter to achieve the frequency and voltage support, which can also be controlled as the power source to balance the instantaneous power and keep the system stable.

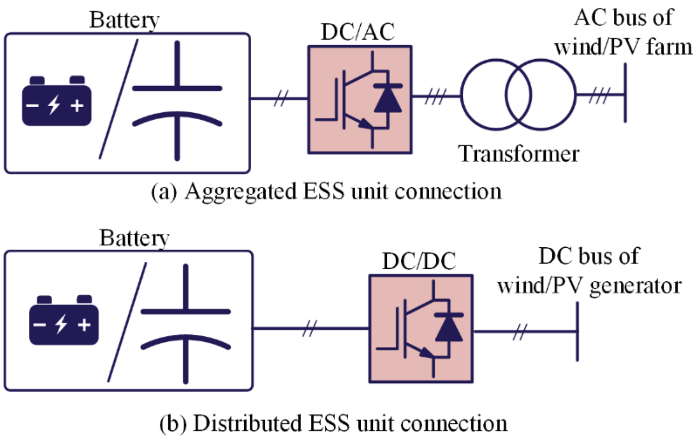


Fig. 17. Configurations for integrating ESS units (a) aggregated ways (b) distributed ways

As it can be seen from the all the topologies mentioned above, no matter for the wind/PV power generation or for the energy storage system, the power electronic converters are indispensable for transforming energy efficiently and integrating to the smart grids stably. It can be clearly seen that the power electronics are the core of the energy transition and the most important part of smart grids, which deserves wide attention and key research.

3.5 Power to X (P2X)

The role of Power to X (P2X) is to achieve new ways of storing energy long term as well as to have a high energy density capability to transportation applications where that are needed – e.g., in heavy trucks, ships and airplanes. The challenge is that the total energy conversion efficiency is much lower compared to storing the electrical energy in batteries – but so far, it is an obvious solution for such applications. Hydrogen can be obtained by different methods – one is naturally to use electrolyzers – as mentioned previously – which is also partly shown in Fig. 18. It can also be achieved by biogas (e.g., from animals and other waste) and other biomass material as well as taken from natural gas (in some cases this is called blue hydrogen).

Fig. 19 shows two "generation" sources in a P2X process including a large number of potential applications. Here both methane as well as methanol are some of the final energy carriers as well as hydrogen itself.

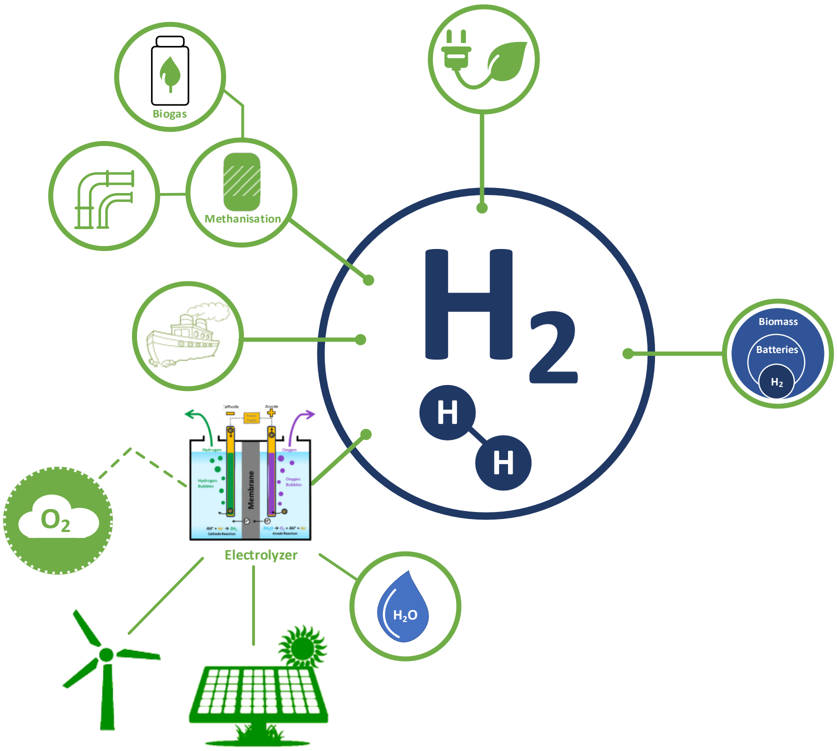


Fig. 18. Role of Hydrogen as a safe, clean and versatile energy carrier.

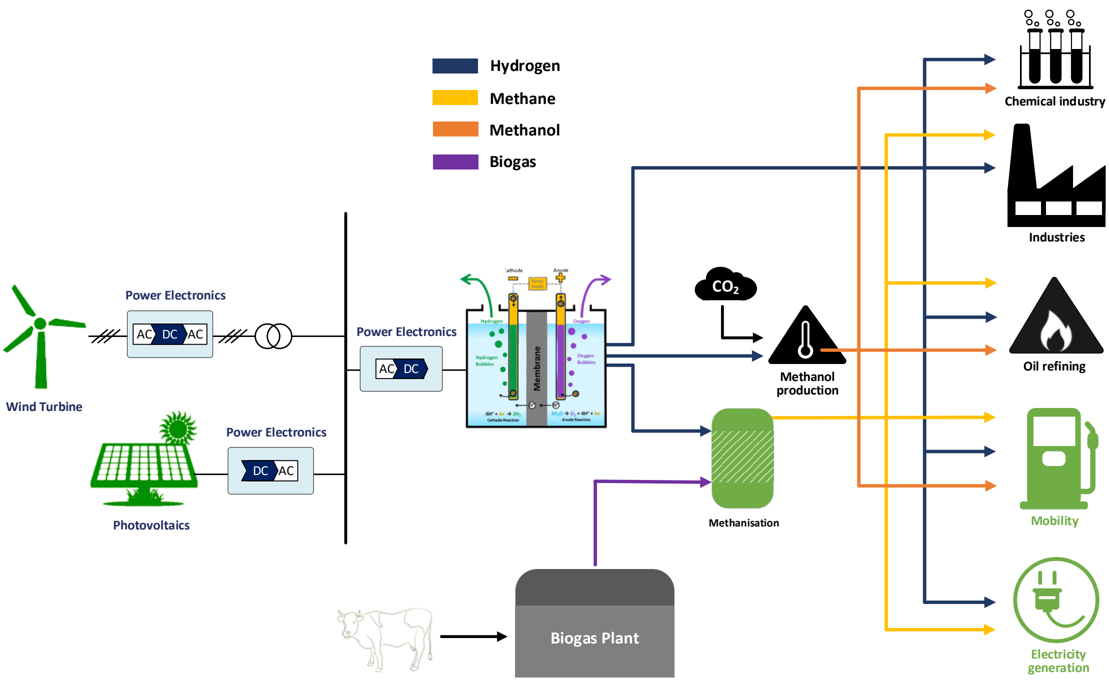


Fig. 19. Principles of P2X. X can be hydrogen, methane, methanol and biogas.

The amount of needed electrical power and energy storage is large in order to be able to cover both heavy transport as well as being a long-term storage. The installations for making such progress are large, and involves large investment cost, high efficiency, obtain good grid power quality and as well as ensuring high reliability. Fig. 20 shows a natural and cost-efficient way to make such an electrolyzer plant. Electrolyzer need most often dc at a relatively low voltage, which means an ac to dc power conversion is needed as the grid is ac. The power source can be directly from the grid or the renewables – then a transformer (50Hz/60Hz) is applied for the step of down-transformation of the grid voltage and afterwards an AC/DC converter as well an output filter are applied to make a high-quality voltage for the electrolyzing process. To ensure a good power quality – an electrical filter is used in combination with a three-wounded transformer (i.e., 12-pulse rectifier transformer). Such solution is cheap for very large plants (GW).

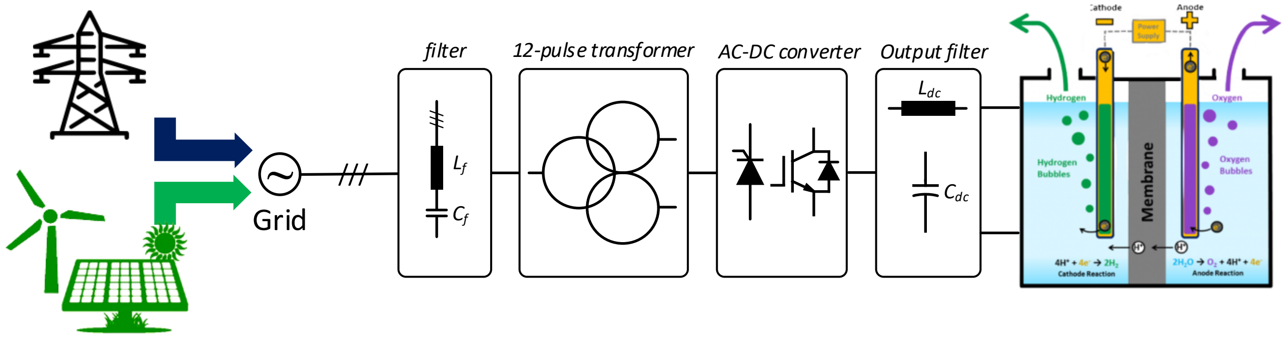
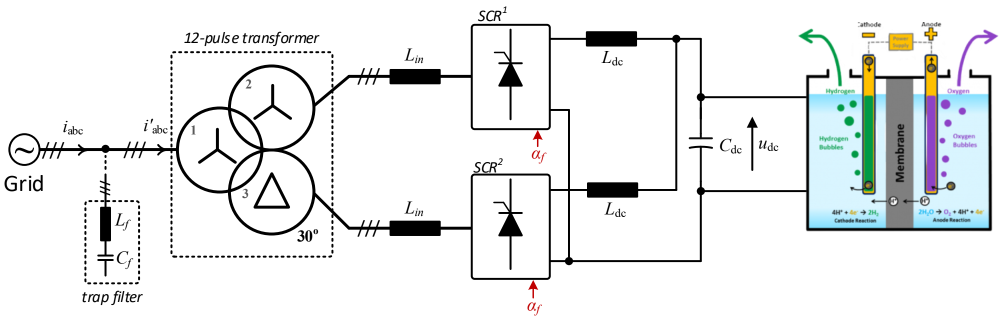


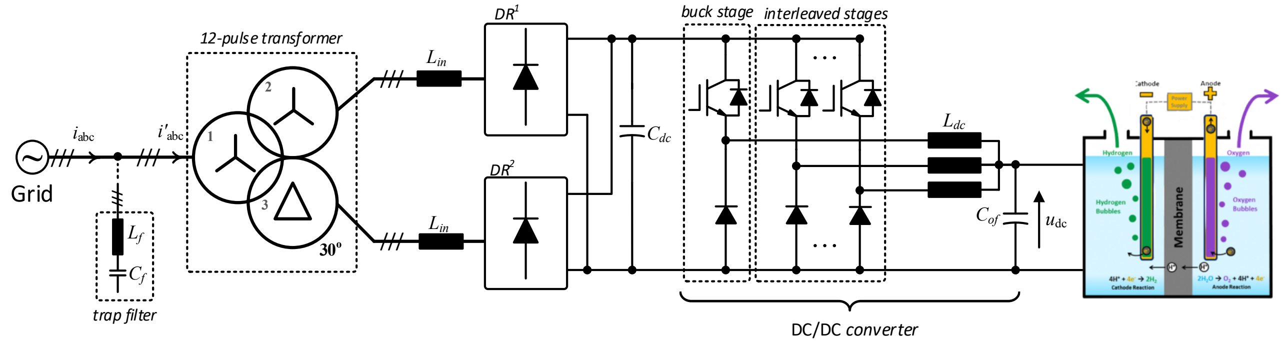
Fig. 20. Schematic of power electronic converter structure for electrolyzer.

The system shown in Fig. 20 can be detailed a little more as at least two principles can be applied to make the electrical power conversion – to control the output voltage and thereby the current in the electrolyzer. Fig. 21(a) shows a very classical way of doing the voltage regulation by using thyristors, while Fig. 21(b) shows a power transistor-based solution where multiple power transistors are operating in parallel and working interleaved.

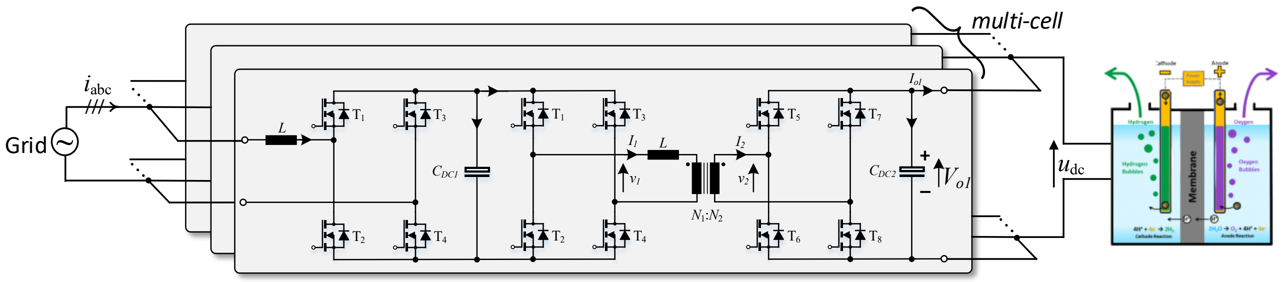
One of the future potential ways of doing this power conversion is to avoid the 50Hz/60Hz transformer and do the power conversion like shown in Fig. 21(c) where instead a high frequency isolation is provided by at the grid side having switching converters doing ac/dc conversion and then provide high frequency dc/dc power conversion where a galvanic isolation is provided. As the operation frequency will be in kHz – the transformer size will be much lower compared to a 50Hz/60Hz transformer. The power supply can have a cell-type structure – where at the grid side – the converters are in series to handle high voltage while at the electrolyzer side – the converters are in parallel to provide the needed current for the electrolyzer process – and a high-quality current can be provided. A heavy transformer is thereby avoided and substituted with high frequency transformer – which is much smaller. The challenge is that more power semiconductor devices are included and thereby it might be more costly. However, the latter solution provides higher modularity and scalability in order to meet different power level requirement based on a power electronic building block (PEBB) concept.



(a)



(b)



(c)

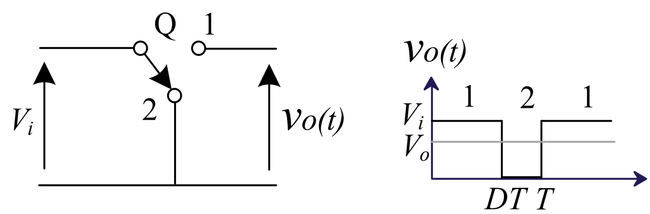
Fig. 21. Different power electronic converter structures for the electrolyzer at a very high-power scale; a) Thyristor-based converter with line-frequency transformer, b) Transistor-based converter with line frequency transformer, and c) High-frequency galvanic isolated controllable modular converter for medium voltage integration.

4 Basic power converters for grid applications

A power electronic converter is made up of at least one power switch, which can be controlled to be switched ON or OFF. This switch ideally has two state: ON state which is short-circuit mode and OFF state which is open-circuit. The basic structure and operation of a converter with a single switch (*Q*) is shown in Fig. 22(a). When *Q* is in position "1", the output voltage is equal to input voltage V_i and when it is in position "2" the output voltage is zero. The output voltage waveform $v_o(t)$ for this converter is shown in Fig. 22(b). If the switch is turned on every *T* second, for the period of *DT*, the average output voltage is thus be equal to:

$$V_o = \frac{1}{T}\left(D \cdot T \cdot Vi + (1-D) \cdot T \cdot 0\right) = D \cdot Vi \qquad (3)$$

T is defined as the switching period and *D* is called duty cycle. Since $D<1$, the output voltage will be lower than the input voltage. This fundamental operation principle can be used to develop different converter structures with appropriate voltage level, AC to DC / DC to AC conversion and so on.



(a) (b)

Fig. 22. Concept of voltage conversion: (a) structure, (b) output voltage.

For instance, Fig. 23(a) shows a converter with two switches. Whenever *Q*1 is ON and *Q*2 is OFF the output voltage is equal to Vi/2. Also, when *Q*2 is ON and *Q*1 id OFF, the output voltage is -Vi/2. Depending on the converter duty cycle, positive and negative output voltage can be generated. Moreover, for a sinusoidal form of *D*, the output voltage will have sinusoidal form. Different modulation shames can be used to generate sinusoidal waveforms as discussed in [36].

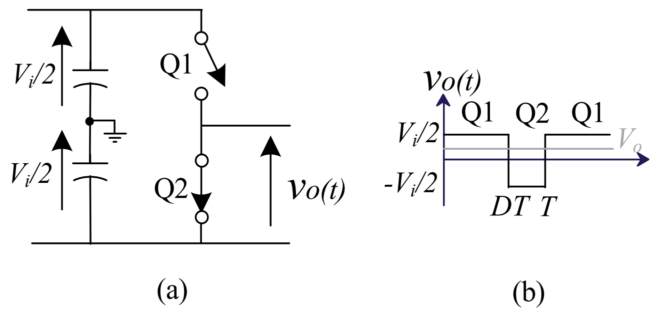


Fig. 23. Concept of voltage conversion: (a) structure, (b) output voltage.

DC to AC converters known as inverters are employed to convert the direct current voltage to the alternating current. A structure of a single-phase half-bridge inverter is shown in Fig. 24(a). The load is connected to the neutral point of the input side. Two capacitors are required to keep the voltage of midpoint constant with respect to the positive or negative pole of input source. However, in most cases, neutral point is not available and using such large capacitors are not applicable due to increasing the size and cost of the converter. Hence single phase full-bridge inverters as shown in Fig. 24(b) can be employed. Moreover, for high-power applications with three-phase loads, three-phase inverters as shown in Fig. 24(c) are used.

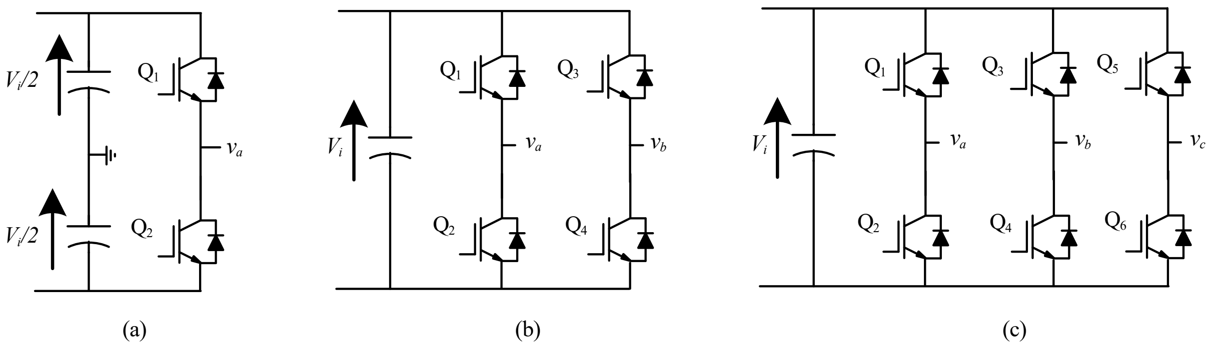


Fig. 24. Two-level inverters; (a) single-phase half-bridge inverter, (b) single-phase full-bridge inverter, (c) three-phase inverter.

In two level inverters presented in Fig. 24, the output voltage is equal to ±Vi/2. However, for high voltage-/high-power applications, multi-level inverters are introduced. The most common structure of multi-level inverters can be categorized as flying capacitor, diode-clamped, and cascaded H-bridge multilevel inverters. Three-level inverter structures are shown in Fig. 25. The first two types of multi-level inverters require dc capacitors to properly form the output voltage, while for the cascades H-bridge, the operation is not dependent on dc capacitors.

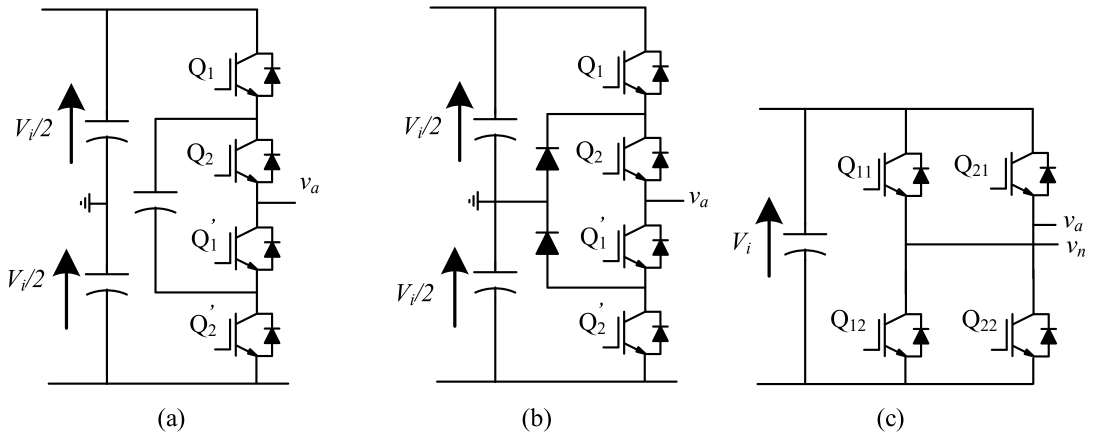


Fig. 25. Multilevel inverter topologies (one phase is shown); (a) three-level flying capacitor, (b) three-level neutral point clamped, (c) cascaded H-bridge.

According to the application and hence the power levels, multi-level inverters can be implemented with different voltage levels. For instance, Fig. 26 shows a five-level cascaded H bridge inverter in which the input dc sources are isolated in each block.

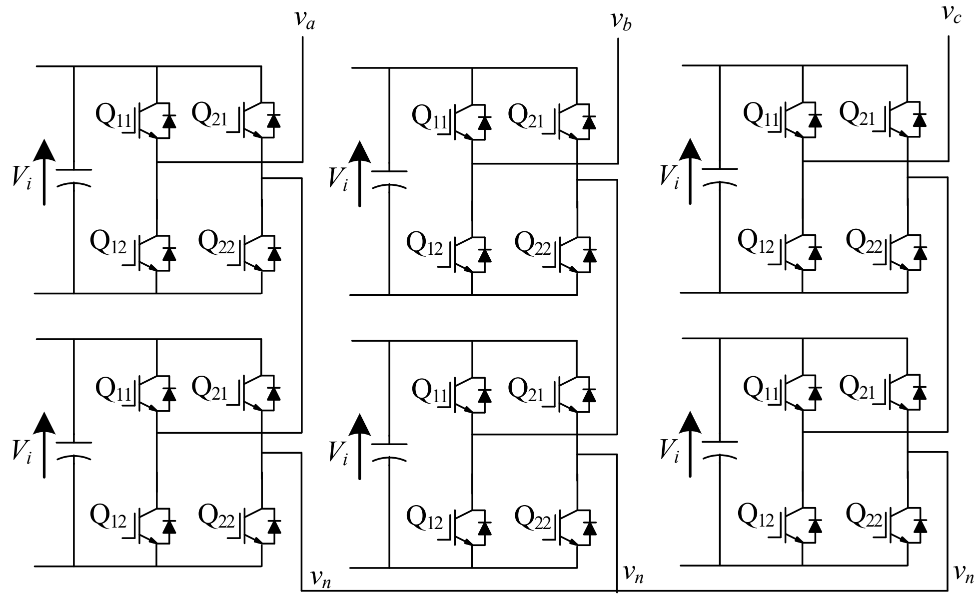


Fig. 26. Three-phase five-level cascaded H-bridge inverter.

Moreover, modular multilevel inverters are presented for very high-power applications. Modular structure, scalability, fault tolerance, high availability and maintainability, and low device ratings are the main advantages of these generation of converters for high power uses. A general schematic of multi-level inverters is shown in Fig. 27. The Sub Module (SM) blocks can have different structures including half-bridge, full-bridge, and etc.

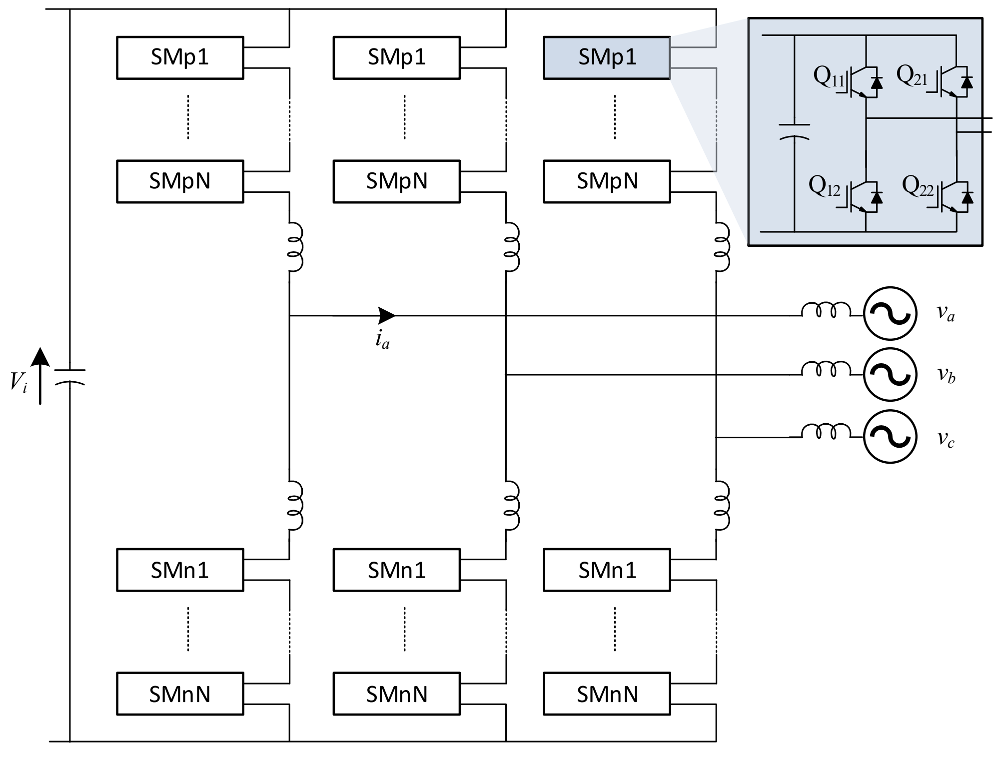


Fig. 27. Structure of modular multilevel converters.

5 Converter control structures

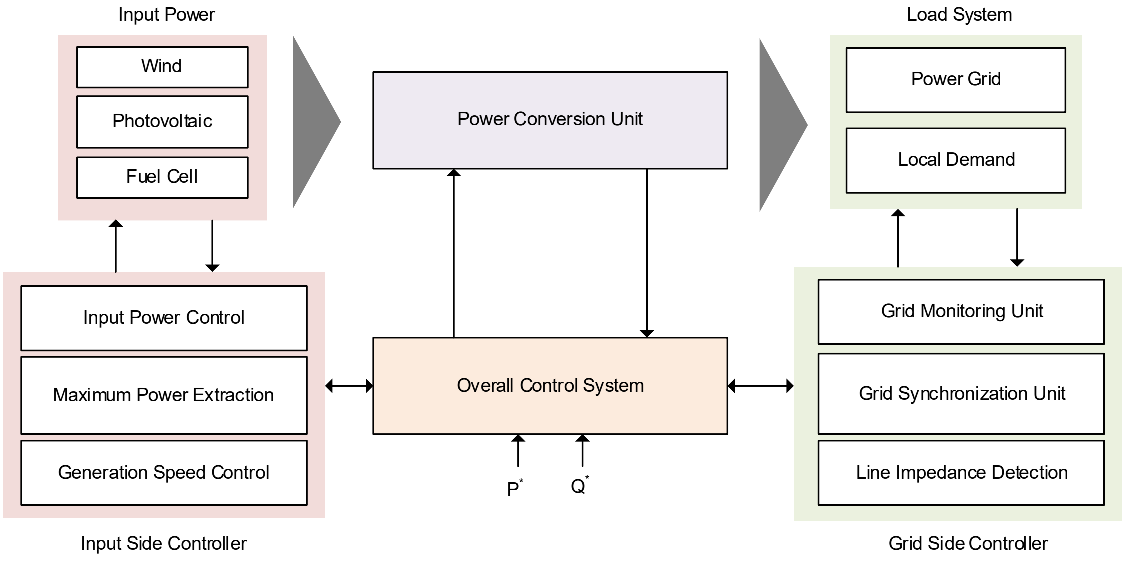


Fig. 28. General schematic of power conversion and control system for grid-tied and standalone units, where P* and Q* are the active and reactive power references, respectively.

A general schematic for distributed power generation sources is shown in Fig. 28. The input power is basically transformed into usable form of electricity via a power conversion unit, which can be controlled and configured as per the requirements in the output. Many general power conversion schemes can be referred from [37]. The generated power can either be provided to the utility grid or local loads, based on the system topology. Finally, the control of the power conversion system can be divided into:

1. *Input side controller:* This controller is responsible for extracting maximum power from the input power source. It can also be used in a flexible manner based on the requirements from the output side to provide grid-supportive services.

2. *Grid side controller:* This controller is responsible for several tasks, such as control of active/reactive power transfer between the generation system and the utility grid/local demand, control of dc link voltage, power quality and synchronization.

The items listed above are some of the basic functions that the grid side converter must have to operate in synchrony with the grid and comply with the grid code requirements. In addition, there are many ancillary services like local voltage and frequency regulation, harmonic compensation, and active filtering, etc., which is usually required by the grid operator [25]. Moreover, the converters are required to ride through grid disturbances, such as, voltage variations and faults. For example, the wind turbines should have a ride-through capability of 0.1 s, when the grid voltage amplitude falls below 25%. To facilitate these functionalities, a fundamental framework for setting the control parameters has been discussed in the following subsections.

5.1 Inner current controllers

The inner current controllers can basically be implemented in various reference frames, such as synchronous rotating (*dq*), stationary (*αβ*) or reference (*abc*) frame. Based on the flexibility and desired application, these frames are consequently selected.

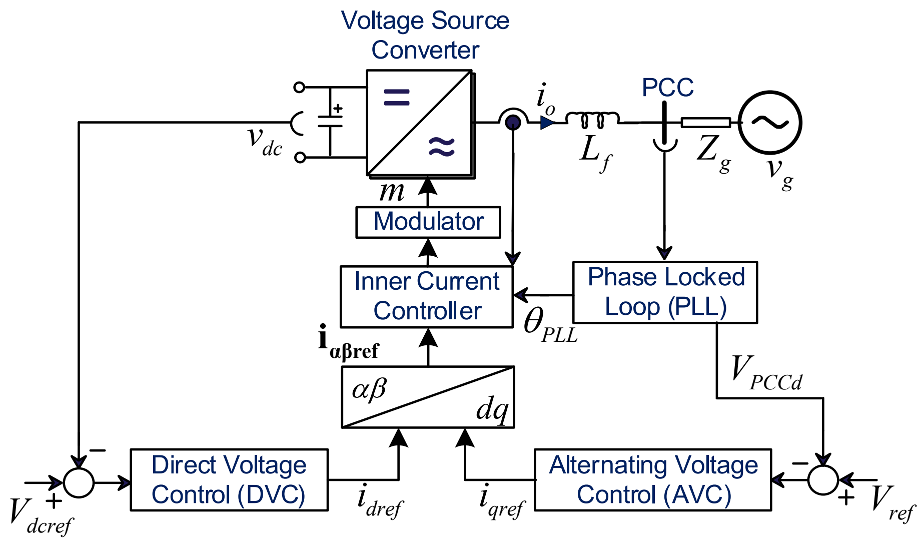


Fig. 29. Main circuit and control system structure of a grid-following converter.

To realize the inner current controller variables as dc signals, *dq* frame is preferred as a convenient platform [99]. Normally, proportional-integral (PI) controllers are associated with this control structure, given by:

$$G_c(s) = K_p + \frac{K_i}{s} \quad (4)$$

where, K_p is the proportional and K_i is the integral gain of the controller, as shown in Fig. 29. Using (5.1), the active and reactive current components are regulated to their respective reference quantities. To improve the dynamic performance, the grid voltage is also used as a feedforward signal. Moreover, the cross-coupling terms as a feedforward reinforce the coupling between the *d* and *q* axis. Basically, these controller gains are governed by matching the filter equations and compensating its effect on the plant. Furthermore, active, or passive damping methods are often necessary to improve the stability. Passive methods are primarily used to design the LCL filters properly [38], model the damping terms, which may affect the volume, cost, and power losses. On the other hand, the active methods allow provisions to add control loops to compensate for the capacitor current [39], [40] or output voltage [41]. They can also provide additional filtering capabilities either with a notch [42] or a lead-lag band [43]. To compensate for various grid harmonics, proportional-resonant (PR) controllers are commonly being used in *αβ* frame, given by:

$$G_{PR}(s) = K_p + \frac{K_R s}{s^2 + \omega_o^2} + \sum_{h=2}^{n} \frac{K_{ih} s}{s^2 + (h\omega_o)^2} \quad (5)$$

where, K_{ih} is the resonant gain at the *h*-harmonic to be controlled, and ω_o is the detected fundamental frequency. In both the cases, the current references are calculated by the outer power controllers, which will be discussed in the next subsection.

5.2 Outer loop controllers

Since two variables (current and voltage) are fed back, the controller design can be made more flexible via cascaded control structures. As shown in Fig. 29, multivariable control is usually set up in a cascaded manner, where the outer loop provides references to a relatively faster inner current controller. It can be seen in Fig. 29 that for a grid following converter, the dc link voltage controller is used as an outer control loop to regulate active power transfer with the grid. Similarly, ac voltage controller is used to regulate the reactive power transfer. However, the control variables change when the outer controller is designed for a grid-forming converter. One of the commonly used cascaded control structure for power electronic converters with LCL filter is the i_o (inner) – v_o (outer) controller, where the converter operates as a controlled voltage source [44].

5.3 Grid-forming and grid-following topologies

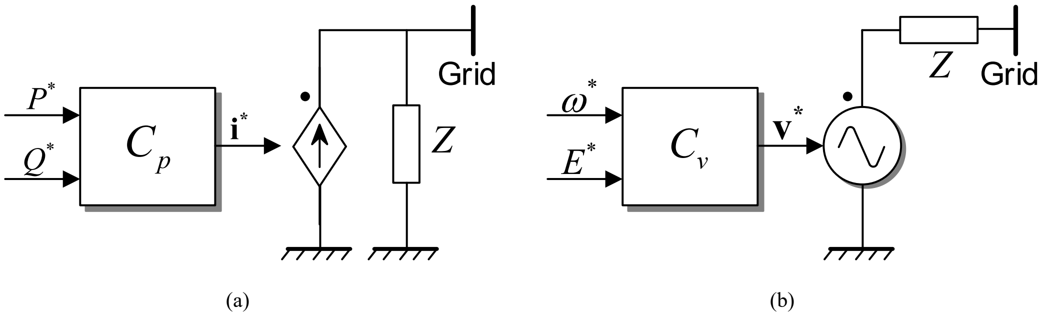


Fig. 30. Single-line diagram of (a) grid-following converter, and (b) grid-forming converter.

Grid-following converter: The function of a grid-feeding converter is to inject a specified amount of current into the grid [45]. Therefore, they can be represented as current sources, as shown in Fig. 30(a). From the implementation point of view, they typically comprise an outer dc voltage control loop, a dedicated synchronization unit, and an inner current control loop with embedded active or passive damping. For generating the current reference, outer power controllers can also be used to supplement the dc voltage controller.

Grid-forming converter: The function of the grid-forming converter is to regulate the local voltage. Therefore, it can be represented as an ideal voltage source, as shown in Fig. 30(b). Due to its stiff voltage regulation, this type of units can be considered as a master in the system that defines the local ac grid [46]. Therefore, the grid-forming VSC does not need to have any power-sharing capabilities and dedicated synchronization. From the implementation standpoint, grid forming VSCs are typically realized by an outer voltage loop and an inner current loop. This functionality can be employed as a basic philosophy in grid connected and stand-alone applications, such as microgrids.

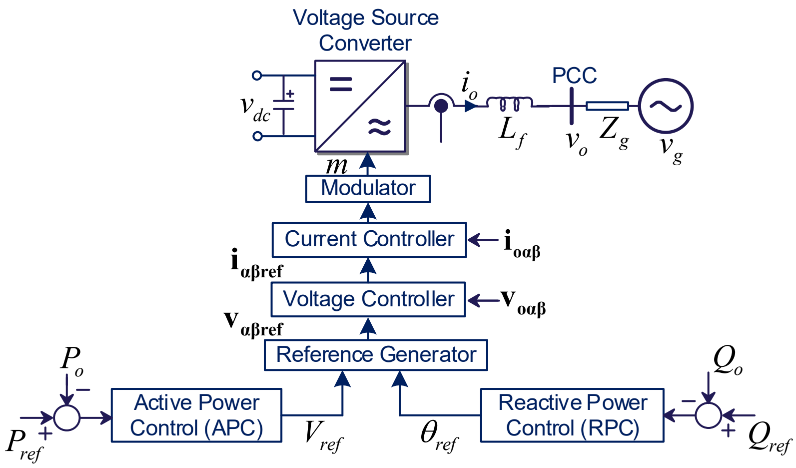


Fig. 31. Main circuit and control system structure of a grid-forming converter.

As shown in Fig. 31, the output active and reactive power is regulated through the active and reactive power controls (APC and RPC) to generate the phase angle and voltage magnitude of the voltage reference, $\mathbf{v}_{\alpha\beta ref}$. It is worth notifying that differently for grid-following converters, PLL is not used for grid-forming converters during normal operations. More details on synchronization of grid-forming converters will be covered in the next section.

5.4 Power electronic-based power system operation

As power systems are being dominated with many power electronic converters, the operation needs to be oriented as per many aspects, such as synchronization, system stability and inertial response [47], [48]. As a result, many hierarchical control structures have been introduced in the literature to accommodate the operation of low inertia systems.

Fig. 32 shows typical structure of APC and RPC, which are responsible for power synchronization, droop control [49], droop control with low-pass filter (LPF) [50] and basic virtual synchronous generator (VSG) [51]. Typically, power synchronization and droop controllers (in Fig. 32(a)) are categorized as first order power control. On the other hand, virtual inertial response can be obtained by augmenting a low pass filter (LPF) with the droop controller and can act as a second order power control. Hence, the inertial emulation dynamics can be used to characterize the dynamics of grid-forming converters.

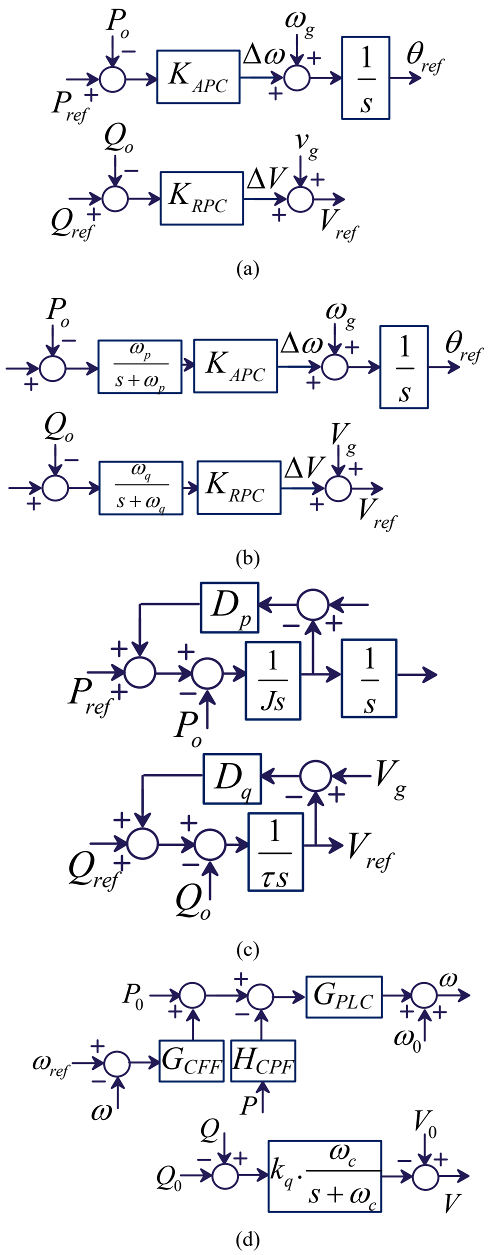


Fig. 32. Typical hierarchical schemes for converters: (a) droop control, (b) droop control with LPF (virtual inertial control), (c) VSG control, (d) generalized droop control.

It is worth notifying that various virtual synchronous generator (VSG) schemes have been recently proposed, in relation with Fig. 32(c). In [52], an additional damping correction term is used to provide additional degree of freedom in adjusting e damping ratio of VSG without affecting its steady-state characteristics. In [53], a power system stabilizer (PSS) based reactive power control of VSG is designed for stability enhancement. While these additional control units alleviate the operation, their fundamental principle lies with the swing equation of synchronous generators, which plays a key role in the operation and stability of power electronics-based power systems. Both the traditional droop control and VSG control have their own advantages, but neither traditional droop control nor VSG control can meet the demand for different dynamic characteristics in grid-connected (GC) and stand-alone (SA) modes at the same time. Rather than using a proportional controller with a low-pass filter, as in a traditional droop control, or fully mimicking the conventional synchronous generator parameters in a VSG control, the active power control loop of the generalized droop controller (GDC) can be designed flexibly to adapt to different requirements [54]. With a well-designed controller, the GDC can achieve satisfactory control performance; unlike a traditional droop control, it can provide virtual inertia and damping properties in SA mode; unlike a VSG control, the output active power of an inverter with GDC can follow changing references quickly and accurately, without large overshoot or oscillation in the GC mode. Moreover, given specific controller parameters, the GDC can function as both a traditional droop control and a VSG control.

6 Power electronics-dominated power system reliability

Basically, reliability is defined as a measure of the ability of an item or a system to fulfill its functionality as intended without any failure with the specified level of performance for a desired time [55]. An electric power network is a large complex system of systems and components that are co-operating together in order to perform power and energy delivery to supply costumers both in short time and also very long period regardless of any planned and unplanned outages in any component. Achieving this performance needs characterizing the power system function into long- and short-term principals. The long-term concept can be evaluated by the electric network ability in supplying its loads at all times which is called adequacy [18], [56], that requires having sufficient facilities with a specified reserve level. Furthermore, the short-term concept known as power system security is evaluated by the electric network ability to withstand unplanned and planned sudden disturbances. Thus, a reliable electric power network needs to have both adequacy and security requirements to supply the customers for a planned time period. As already discussed, the system adequacy will be assured by proper planning, design and installing appropriate facilities in a long period of time, while the system security needs to be guaranteed by appropriate solution to strengthen the system stability.

As shown in Fig. 33, planning and operation of electric power systems are hierarchically performed in various phases with respect to the time. Planning is mainly done in three phases in a long time, short time as well as operational planning phase [16], [17], [57]. As already discussed, the long and short time planning is associated with the design and facility planning, including development of the power network with new technologies, expanding transmission systems, expansion of generation systems, and extending distribution networks, for supporting the customers. Moreover, the operational planning is performed within the operation from the hour of delivery to a seasonal planning in order to used the existing generations and other facilities to supply the customers. As shown in Fig. 33, the adequacy is hierarchically analyzed in three levels in the traditional power networks with a top-down structure. In the Hierarchical Level I, the adequacy of the generation system capacity is analyzed, in the Hierarchical Level II, the adequacy of the composite generation and transmission systems is evaluated, and the distribution system adequacy is addressed in Hierarchical Level III [18].

There are various uncertainties in power grids affecting the reliable operation of power systems including load forecasting uncertainty, renewable generation uncertainties, unscheduled outages, grid faults, etc. The uncertainties coming from load and renewable generation forecasting are supported by (1) the stored energy in the rotating mass of synchronous generators known as primary reserve, and (2) generators participating in spinning reserve known as secondary control. On the other hand, the unplanned events occurrence happening like the loss of a large generation unit, outage of a line or a transformer can induce serious problems to the stability and adequacy of power systems. Moreover, they can lead to overloading, overvoltage in the system equipment as well as stability issues. Therefore, a reliable power system needs to withstand any disturbances to reach a specific security level [19], [20].

The system security could be ensured by either deterministic approaches or probabilistic methods with respect to the probability of any contingency and the corresponding consequence As shown in Fig. 33,The power system security is analyzed in two main concepts addressing dynamic/transient and static phenomena [19]. In the static security analysis, the voltage and thermal limit violations are explored to prevent overloading and overvoltage in any equipment. Moreover, before reaching a steady state condition, the overall stability of power system needs to be analyzed and guaranteed.

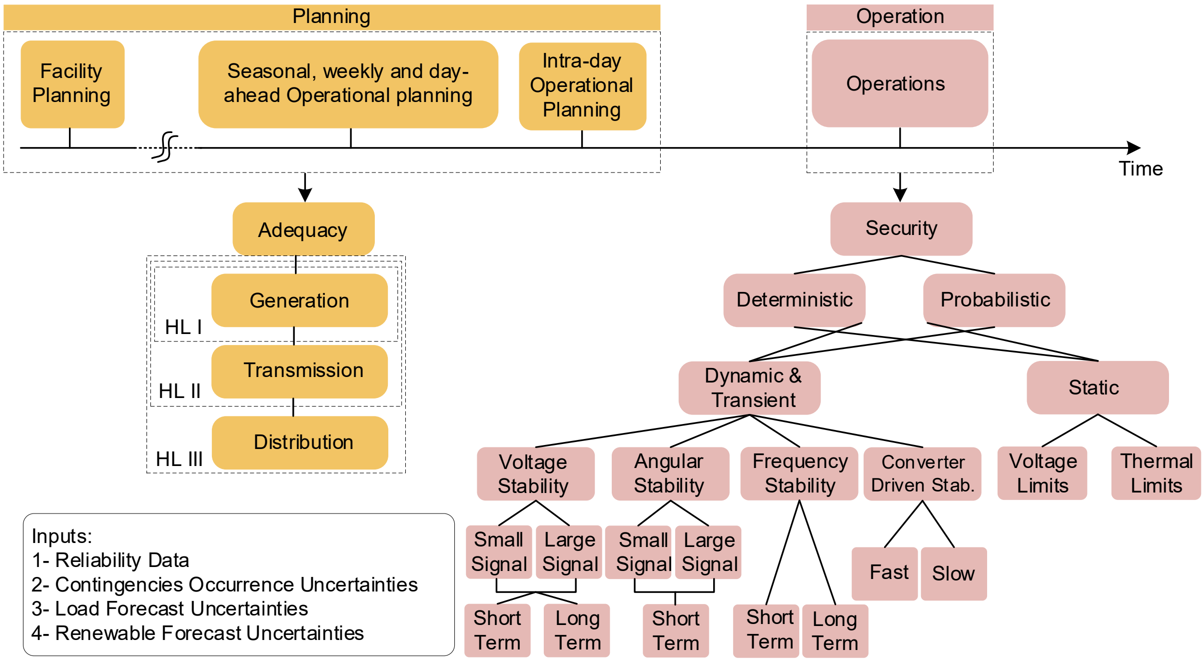


Fig. 33. Reliability assessment concepts in power electronics-dominated power systems. HL: Hierarchical Level.

6.1 Modern power system reliability assessment

The reliability modeling in power electronics-dominated power systems could hierarchically be done in system, subsystem and component levels as illustrated in Fig. 34 [58]. According to this method, first, the system is analyzed in power system level using power and energy management methods to find out the electrical loading of different subsystems. Next, in the sub-system level, the electrical loadings are translated to the thermal loading of different devices and components in each subsystem like a converter. In the device level, the failure rate of components is modeled considering both those are related to random chance failures and those are associated with component gaining in the component level, as shown in Fig. 35. Then, in the sub-system level especially power converters, the corresponding availability is modeled using the failure frequency of its components. Finally, the availability of subsystems is employed in the system level reliability assessment process to evaluate the overall system performance.

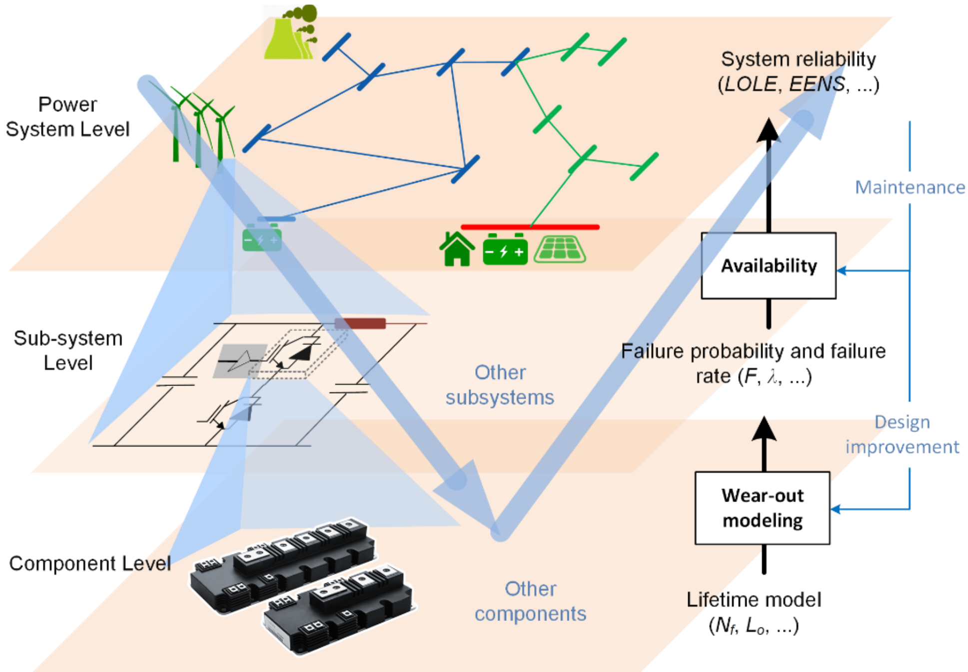


Fig. 34. Model-based reliability assessment in power electronics-dominated power systems.

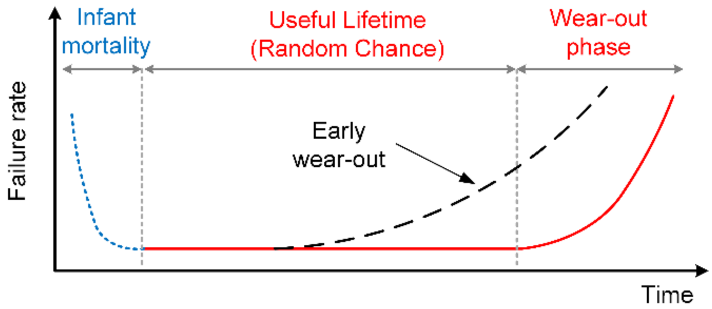


Fig. 35. Failure function of a system including infant mortality, random chance failures and wear-out failures.

6.1.1 Power system reliability

Reliability of electric power system is evaluated by probabilistic measures showing its ability to support the customers such as Loss Of Load Expectation (LOLE) and Expected Energy Not Supplied (EENS) [18], [56], [59]. The LOLE is the number of hours or days per a specified time period usually one year in which the system demand is supported because of the generation/facility shortage, and it is obtained as:

$$LOLE = \sum_{i=1}^{n} P_i \cdot (C_i - L_i) \tag{6}$$

where C_i is the available power capacity in load level i, L_i is the forecasted peak load either hourly or daily, P_i is the portability of loss of the load L_i [18]. Furthermore, EENS denotes the amount of curtailed energy due to the lack of sufficient generation/facility and it is obtained by using (7) [60].

$$EENS = \sum_{i=1}^{n} P_i \cdot E_i \tag{7}$$

in which E_i is the amount of curtailed energy.

Fig. 36 shows the procedure of the reliability assessment in modern power electronics-dominated power systems [61]. First, the reliability of subsystems is predicted. As the power converters are the most failure prone subsystems in power system, its reliability is modeled with more details. The process of power converter reliability modeling is addressed in [62]. Afterwards, the availability of a single unit renewable resource, e.g., PV array or wind turbine, is estimated based on failure frequency of the corresponding components. Afterwards, the reliability of single generation unit is modeled based on the single unit reliability model and the renewable uncertainty. In the case of HVDC links between power plant and the main grid, the reliability model of HVDC system is modeled. Thereafter, the reliability of the whole renewable power plant is evaluated. Moreover, the availability of the traditional generators and the bulk power system is modeled considering the failure characteristics of each individual units according to [18]. After obtaining the reliability model of generation system, the whole system reliability is obtained using (2) and (3) by convolving load characteristics and generation reliability mode. In the following, this procedure is explained in detail.

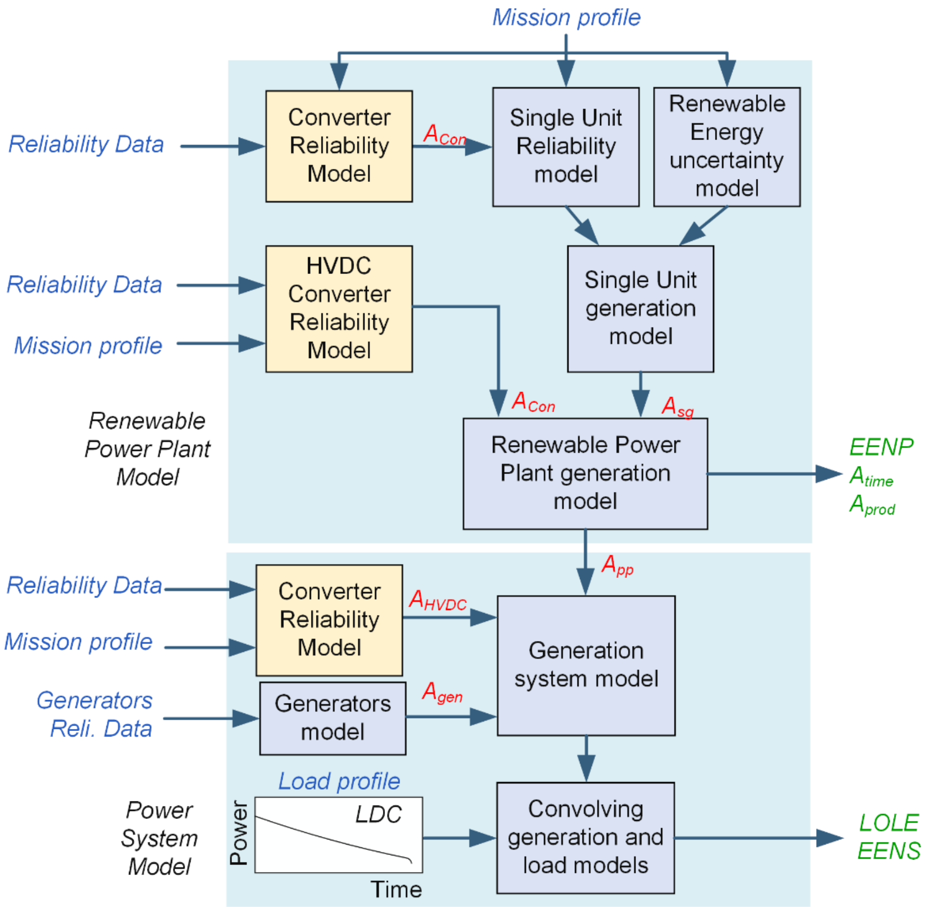


Fig. 36. Reliability evaluation in power electrics dominated power systems.

6.1.2 Reliability of renewable power plants

The performance of a renewable-based power plant can be evaluated by its availability [63]–[65]. There are two availability measures which are basically defined for wind power plants: time-based availability A_{time} [63] and production-based availability A_{prod} [64]. However, the definition is general and applicable for any renewable system. The time-based availability is defined as the amount of time the power plant is not operating divided by the whole operating period using:

$$A_{time} = 8760\left(1 - \frac{Unavailable\ time}{Available\ time + Unavailable\ time}\right)[h/y] \quad (8)$$

This index measures the unavailable time, while it is not measuring the amount of lost energy due to the power plant unavailability. Thus, an energy-based availability measure is defined as:

$$A_{prod} = 1 - \frac{Lost\ production}{Actual\ energy\ production + Lost\ production} \quad (9)$$

where it is based on the amount of lost production.

6.1.3 Availability of renewable units

To predict the power plant availability, the single unit availability needs to be modeled. As the renewable generations are climate-dependent, their output power also depends on the wind speed or solar irradiance. Moreover, the single system is made up of different parts such as power converter, control, transformer, etc. Therefore, the availability of a single unit needs to be modeled taking into account the uncertainty of prime energy and availability of the subsystems. One method to model the of renewable power availability is to discretize the generated power by the single units into some discrete states. For example, in a single unit with rated power of Pn, its output power can be divided into 0, P1, P2, P3, … Pn as shown in Fig. 37. The state probability is calculated by convolving the probability of renewable power distribution with the characteristic curve of renewable generator like wind turbine or PV power plant [66]–[68]. Each state is available if the unit is operating. For instance, the probability of generating P2 is the probability of having P2 from prime energy times the availability of the generations system including all components. among the different components, power electronics converters are serving as the frequent source of failure and hence affecting the whole system reliability. In the next section, the reliability of converters is explained.

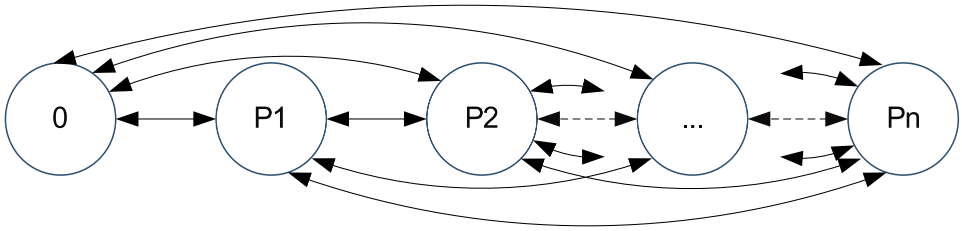


Fig. 37. A single unit renewable source availability model.

6.2 Power converters availability

A converter is available if and only if any of its components are available. Thus, the converter reliability can be modeled by the reliability of its components as shown in Fig. 38(a). Hence, the overall availability of the converter is calculated as:

$$A_{con}(t) = A_{SW}(t) \cdot A_{Cap}(t) \cdot A_{OC}, \qquad (10)$$

where, $A_{con}(t)$, $A_{Cap}(t)$, $A_{SW}(t)$ and A_{OC} are the availability index for the converter, capacitor (Cap), power switch (SW) and Other Components (OC).

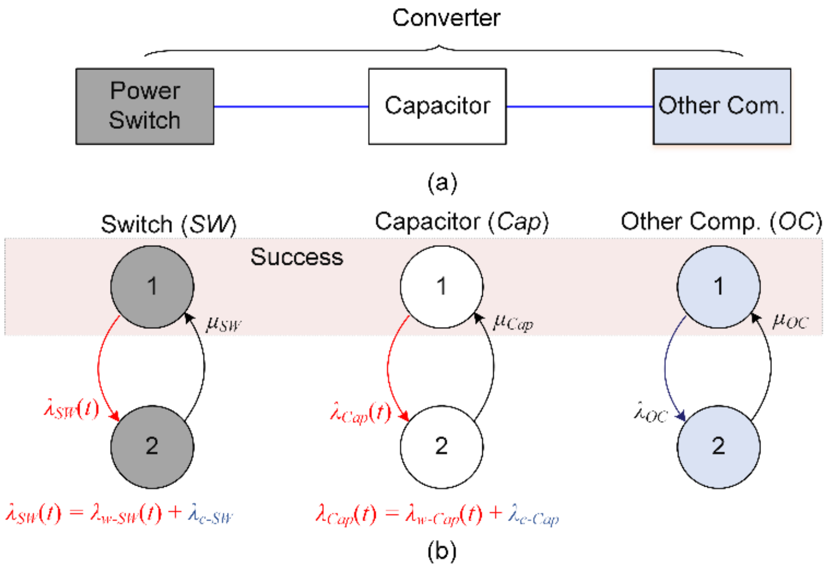


Fig. 38. Availability model of a power converter; (a) state space representation with three major parts, (b) Markov model for switch, capacitor and other components.

In practice, due to the regular maintenance in the system, the failure rate of components is considered constant with the assumption that the item is operating in its useful life as shown in Fig. 35, thus, aging rarely happens. Availability of the components with constant failure rate, where the time to failure is associated with an exponential distributed, is modeled using the Markov Process (MP). According to the concept of MP, system has two states of either operating or being down. The availability, A is thus defined as the probability that the component is in operation state, which is calculated as [69]:

$$A = \frac{\mu}{\lambda + \mu} \qquad (11)$$

in which λ, μ denote the failure rate and repair rates.

Since capacitors and power switches are prone to aging failures [70], [71], their availability can bot be modeled by using MP. The random chance failures in power devices and capacitors are usually caused by abnormal operation and sudden over-stressing the components like overvoltage, overcurrent occurrence. However, the aging failures usually occurs in the long-term by degradation of the component materials. As a result, failure causes are basically independent. Thus, for these components, the failure rate on useful life failures and aging failures can be decomposed into two terms including constant and time-dependent terms. Therefore, the component is available if and only if failure in both terms does not occurred. Thus, the overall availability $A_t(t)$ is calculated as:

$$A_t(t) = A_c \cdot A_w(t), \qquad (12)$$

in which, $A_c(t)$ is related to the random chance failures, and the $A_w(t)$ is the availability due to the aging failures. There are different approaches to predict the availability due to the aging failures. A comprehensive overview is proved in [72].

7 Power electronics-dominated power system challenges

The power grid modernization in will bring new challenges to efficient and reliable operation of modern electric networks. These challenges are summarized in Figure 39 and are discussed in the following.

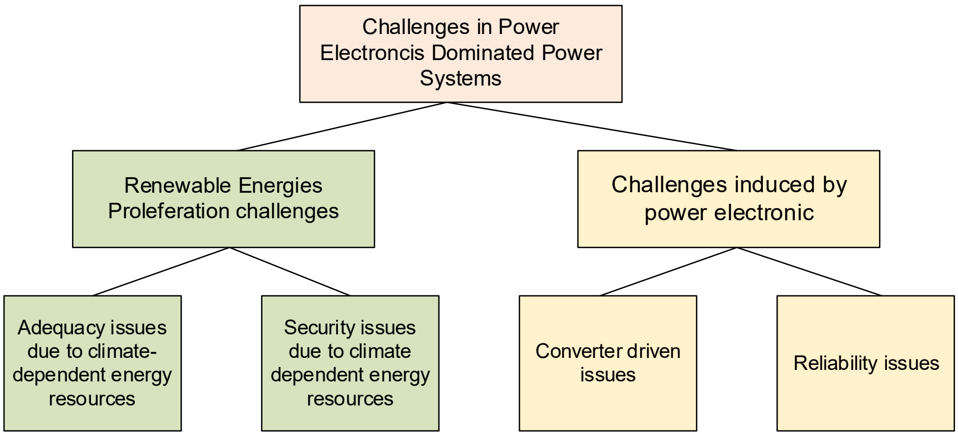


Fig. 39. Power electronics-dominated power system challenges

7.1 Renewable energies proliferation challenges

Solar and wind energy generations have been gaining more and more attention. The penetration level of solar and wind generation is remarkably increasing worldwide. Integration of high capacity renewable energies despite decreasing carbon footprint, poses technical challenges to the power systems with full renewable-based generations. Two main technical challenges are the climate-dependent generation uncertainty and low inertia.

7.1.1 Adequacy issues due to climate-dependent energy resources

The adequacy challenges are raised by the variable characteristics of renewable-based power plants, which makes load generation imbalance in the power system. To address load-generation imbalance, the entire power system needs to be adequately designed considering the renewable generation, storage units, protection, control and so on. Therefore, the power system adequacy can be assured by employing proper storage systems, interconnecting to the neighboring power systems hydropower plants, and de-rating renewable-based generations.

Utilizing large-scale energy storage units is one of the reliable approaches to facilitate the heavy uptake of renewable-based generation systems. Beside the costs, the basic and technical challenges that this approach may face would be the large size, and placement strategies of different the storage systems with different technologies. These two factors are of high importance to ensure the system reliability and resiliency subjected to any uncertainty resulting in grid splitting. Therefore, the design, placement and technology selection for the utility-scale storage systems needs to be adequately carried out.

Moreover, interconnection to the power systems of neighboring countries using HVDC transmission systems can aid heavy uptake of renewable generations by providing proper grid services. Thus, smart control of HVDC systems to support the grid adequacy is necessary for electric power networks with full renewable-based generations. However, reliability support from neighboring networks may introduce marketing challenges especially with high level of renewable energies. Inter country HVDC systems can also help incorporating different types of renewable generations to compensate the load-generation imbalances. As an example, interconnection of the North-Europe with high wind power potential to the South-Europe with high solar power potential with respect to the reverse seasonal characteristics can facilitate reshaping the generation profile. Furthermore, this can decrease the size of utility-scale storage systems since the availability of the generation system is increased.

Moreover, powered-rated operation of renewable generations can facilitate moving toward full renewable-based generation systems, while it might not be an economical approach. Hence, there could be a compromise between the loss of energy due to de-rated operation of converters and the power system reliability enhancement by providing grid services like frequency regulation in the de-rated operation mode of renewable generations. This will also introduce new market issues.

7.1.2 Security issues due to climate dependent energy resources

Synchronous machines with the help of the inertial response that is based on the stored energy in the rotating mass help demand generation balance inherently. The frequency violation induced by large load/generation connection/disconnection will be sensed by the droop control unit, known as primary control, of the generator governor. Thereafter, the frequency variations will be restored by the secondary control to a reference frequency. Furthermore, the primary control compensate the demand-generation imbalance with the help of primary reserve in short-time. Afterwards, the generators that are participating in primary reserve are released by the secondary control by using the generation in the spinning reserve. Moreover, the load changes in the long-term are compensated by the generations participating the tertiary reserve.

By increasing the integration of the green technologies such as PV and wind power plants, due to the lack of rerating energy coupled to the power system, the inertial response support become weak. Low inertia, will increase the rate of change of frequency (ROCOF), thus, may functioning the protection devices. In power electronics-dominated power systems, it may in turn lead to cascaded outages. Therefore, to maintain the stability and reliability of modern power systems, frequency supportive capabilities need to be implemented in renewable generations. This can be done by implementing droop controllers in in the control systems of converters so the renewable units will mimic the synchronous generator behavior. Of course, this requires the renewable generations to operate in the de-rated power to support both frequency increase and drop.

7.2 Challenges induced by power electronic

Power electronics are becoming the backbone of the energy systems for implementing microgrids and integrating more and more renewable generations. Even though power electronics introduces better controllability, flexibility and operability, they can induce some technical issues at different aspects. A main challenge introduced by increasing integration of power electronic converters is the stability issues coming from interactions between converters and other components and controllers such as, passive components, mechanical systems, and other converters. The next issue is the reliability of converter components which are prone to wear-out.

7.2.1 Converter driven issues

In order to properly operate power electronic converters, various control units such as inner current control, grid synchronization control, AC and DC voltage regulators, active/reactive power controls, and frequency regulator are implemented in each converter depending on its function. These control units have different dynamic characteristics in a wide range of frequency from a few Hz up to several kHz, and may interact with other power system components and/or their control units [16], [73], [74].

In traditional power networks, the interaction of different components in power system side with the torsional modes of turbine-generator in synchronous machines are the most dangerous interactions. This may cause sub- and super-synchronous oscillations in the shaft of turbine and cause fatigue in long term. As an example, the interaction of series capacitive compensation and torsional modes of synchronous generators will result in sub-synchronous resonance (SSR). Moreover, sub-synchronous oscillations can be the result of interactions between control system variable speed drives, HVDC systems, and Power System Stabilizers (PSS) with the torsional modes of synchronous generators. These oscillations may occur between power electronic converters and the other converters or series compensated systems as well. Moreover, interactions of a power converter and other converters, torsional modes of generators and motors, and passive components can cause super-synchronous oscillations.

Except the interactions between mechanical torsional modes and series compensated system, the other types of interactions are occur between the control of at least one device, for example a converter [75], with other parts. The interactions can cause stability issues in the system with a poor damping factor. This instability can cause both low frequency and high frequency oscillations in the system [16], [73]–[75]. These stability challenges are associated with the cross coupling among converters (either their control or passive components) and other converters, passive components, power lines and turbo-generator trains. This type of stability becomes more severe in power electronics-dominated power systems, and it may lead to disruption in the power delivery [73], [76]–[79]. Hence, the overall security of the system may be affected.

This problem can be severe once the operator intends to evaluate the overall security of the power system considering various stability issues and any credible contingency. Accessibility to the control parameters of each power electronics units from various manufacturers with different characteristics is one of the challenges. This will cause interactions between them and other components. Moreover, the interactions depend on the control dynamics. Therefore, the evaluation of the security of such a complex system will be a difficult task especially with high uptake of power electronics converters. Moreover, with high penetration of converter-based generation units, stability assessment considering any credible contingencies are time consuming. However, the security assessment needs to be performed in a limited time by the operator considering various types of converter-driven stability issues.

7.2.2 Reliability issues

Based on various studies, the power converters are most failure components in many applications [70], [80]–[86]. The operating and climate conditions are two main affected factors on the reliability of converters[58], [87]–[94]. Furthermore, the capacitors and semiconductor devices as the most failure prone components are subjected to aging failures because of the variable and carriable operating and climate conditions comprising power loading of converter, vibration, ambient temperature, humidity. [87], [93], [94]. Therefore, the converter failure rate is time-variant and the life expectancy of the components is limited. Moreover, the converter life expectancy depends on the climate and operating conditions. As a result, mission profile analysis should be performed for converter reliability modeling [87], [91].

After extracting the lifetime variables profile for key components, the residual life of components can be predicted using corresponding lifetime models associated with a certain failure mechanism. Since, the electro-thermal and lifetime models are facing stochastic and epistemic uncertainties. the must be calculated. The Monte Carlo simulations or theoretical analysis considering the uncertainties can be implemented to calculate the probability of the device lifetime [91]. Therefore, the lifetime and distribution of converter can be obtained using mission profile analysis thorough Monte Carlo simulations. This process is time-consuming as it requires detailed electro-thermal model of components as well as due to the Monte Carlo simulations. While it is a suitable approach in in power converter level [95], it will require high computational load for extensive power systems .

In power system analysis, the converter reliability is modeled as a random chance failure with constant failure rate using historical data [18], [66], [96]–[103]. Utilizing constant failure rate for converters in reliability modeling will introduce erroneous risk prediction in power system reliability assessment [104]. Therefore, non-economic decision-makings in planning and operation of electric power system with more power electronic converters can be achieved. With the aim of accurate reliability prediction of power electronics-dominated power systems for system-level analysis, the converter reliability requires to be involved in the power system reliability assessment model. This can impact the overall system reliability in two areas. First, the limited life expectancy of power converters should be considered during facility planning phase for optimal replacement of converters employing suitable maintenance strategies. Second, in the operational planning the time-varying and condition-based failure rate of converters should be considered. Thus, depending on the usage, the power system reliability and performance may be affected by converter reliability [58], [104].

7.3 Reliability enhancement strategies

As already discussed, the reliability of power electronics-dominated systems can be explored in three different levels of component, sub-system and system levels [61]. The component-level is attributed with the component of each sub-systems like power transformers, power electronic converters, solar arrays, wind turbines, and protection relays. In particular, the converter components include switches, capacitors, gate drivers, control unit, cooling system, and so on. Improving the reliability in this level can be to reinforce the life expectancy of any devices by analyzing the physics of failure mechanisms.

In the sub-system-level, for instance, the power electronic converters reliability is in correlated with of the lifetime of converter components and operating conditions. Design for reliability in power converters considering a specified mission profile can guarantee an acceptable long-term performance with a desired reliability [91], [105]. In this strategy, the converter component selection and sizing will be done according to the applied stress in a desired application. Different factors can impact a converter reliability [70], [80], [81], [106] including its topology [105], application [87], control strategy [87], [107], operating and climate conditions [87], [108]. Therefore, the application of converter, its topology and control methods must be considered in design level to enhance the converter reliability.

In the system-level, availability of each sub-system is important. Availability is related to the failure rate and applied maintenance strategies. The availability can be enhanced by reducing the failure occurrence and/or maintenance times. This requires modeling the reliability of components. For instance, as already discussed, the converters are failure prone units in power systems, and hence their reliability modeling is required to either reduce the failure occurrence [87] or planning for proper maintenance times [61]. Thus, the power and energy management procedures regarding to the reliability of generation units and transmission utilities can considerably improve the overall system reliability [58].

From the security stand point, it is crucial to appropriately model the impacts of converters on the stability of system. Power converters are facing with wide range of stability issues in power systems due to the electro-mechanical and electro-magnetic interactions [73]. Implementing proper controlling system and output filter design including the interactions with different parts of power system need to prevent stability issues in power electronics-dominated grids.

8 Summary

Moving toward green energy technologies will introduce more technical challenges to the modern interconnected energy systems with power systems. To address these challenges, it is necessary to understand the basics of power systems and the new technologies integrated to the power systems. Among the emerging technologies, power electronics play a significant role in various applications. Depending on how to design, control and operate the power electronics, they can strengthen or deteriorate the performance of the whole system. This paper has provided an overview on the modern electric energy systems with more power electronics integration in generation, operation and control perspectives. The basics of power systems have been introduced. Furthermore, the fundamentals of transition from traditional centralized power systems to modern power systems are discussed. Dominant clean energy generations have been introduced. Moreover, the basics of power converter topologies and control structure have been explained. Moreover, the concept of reliability assessment in power electronics-dominated power systems have been discussed.

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