Photovoltaics in Microgrids

An Overview of Grid Integration and Energy Management Aspects

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The microgrid vision contains several aspects, and a commonly admitted one is a portion of grid with its own means of production and energy flow controls. Photovoltaic (PV) generation is geographically the most distributed means of electricity production. In this sense, the integration of PVs in microgrids seems natural. The intermittency of PV generation can be compensated not only by using energy storage technologies but also by demand-side management and exchanges with other power networks: the main grid and surrounding microgrids. Many aspects still have to be investigated in the fields of power electronics, information communications technologies (ICTs), protections, and power quality (PQ) issues, to make this association a reality.

Definition of Microgrids

The integration of intermittent energy sources in power grids has accelerated the necessity of energy management in a multigeneration source network to ensure a reliable and continuous power supply. The microgrid concept illustrates these issues by associating a variety of distributed energy sources and loads in a power network capable of an islanding operation with the main grid [1]. The deployments

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of microgrids are expected to impact the economical, environmental, and electricity supply quality and reliability aspects [2]. Indeed, the coordination strategies of controllable local grids can have many drivers, such as reducing carbon dioxide emissions related to energy generation, guaranteeing a low cost of energy, and maintaining high continuity and/or quality of electric supply. Although no current international consensus on the definition has been established, microgrids refer to a small scale of the power network, with voltage levels used on the distribution network (≤20 kV) and power ratings ranging up to 1 MW [3]. However, some microgrid projects in islands tend to exceed these average values.

The off-grid operation mode provided by the microgrid involves the management of several generation sources, both renewable and carbon emitting, combined with conventional and controllable loads. Power electronic and electricity storage devices (such as batteries, flywheels, and ultracapacitors) are also used to manage power fluctuations and supply energy during the transient and steady-state operation of the islanded microgrid. A large variety of devices connected to the local network may combine alternative and dc operating equipment. Hence, power electronic converters are used to link these elements of various frequencies (nature) to ensure correct operation of generation, storage, and nonconventional loads.

Today, microgrids use ICTs, such as sensors and smart meters, to evaluate the power flows and balance production and consumption using local energy management systems (EMSs). An EMS includes hardware and software capable of monitoring and controlling power generation units and unconventional loads for safe grid operation and quality of supply.

Hence, the overall management of a microgrid involves several layers: the EMS, distributed control devices, power electronic converters, power generation units, loads, and interactions with other power clusters as shown in Figure 1.

The power generation systems considered in microgrids concern both renewable sources (PVs, small wind

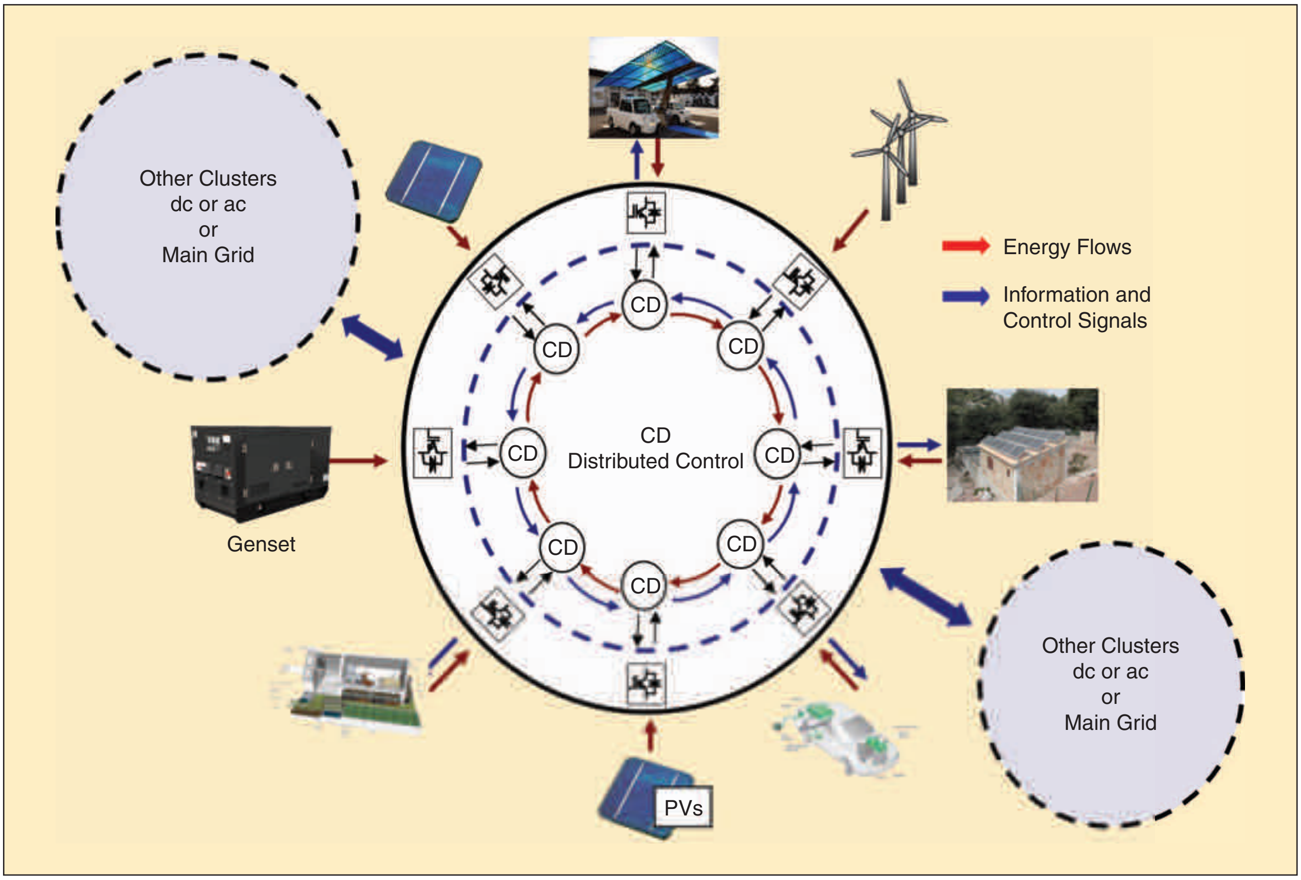

FIGURE 1 – An overview of the microgrid concept. (Photos courtesy of Wikipedia and Wikimedia Commons.)

turbines, hydrogen fuel cells, and small hydroplants) and fossil sources (diesel engines, gas microturbines, gas fuel cells, etc.). The power generation units may be building integrated, rooftop installations, residential, or on field.

Building-integrated generation units use technologies that are directly mounted on the structure of the building: walls, roofs, and solar shades. Building-integrated sources most commonly use solar PV modules for their ease of integration in structures and aesthetic attributes; however, some architectural projects have considered small wind turbines integrated in tall office buildings, such as the Bahrain World Trade Center [4].

Rooftop installations involve placing generation units on top of existing structures such as residential houses, industrial factories, or commercial sites. These mainly concern PVs and small wind turbines.

Solar parking lots, where cars are parked in the shade provided by PV modules that generate electricity either for load supply or electric vehicle (EV) charging, can be integrated directly in the shade-providing structure or mounted on rooftops.

More futuristic concepts tend to implement generation units in the home, such as the Smart Home concepts currently being developed in Asia. Households are equipped with outdoor heat combined generation units such as gas fuel cells, microgas turbines, or small wind generators. Furthermore, such smart homes include local energy storage technologies in battery storage rooms and EVs (and plug-in hybrid EVs) connected to the home (vehicle to home) for periodic and short energy storage usage [5], [6].

The generation sources with the greatest power ratings are generally on field, in other words, in areas reserved for energy generation separated from buildings. These include diesel engines, gas turbines, large PV installations, small hydropower plants, and wind farms of several hundred kilowatts.

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PV Integration

PV Grid Integration

In 2013, the estimated cumulated PV capacity in the world reached 134 GW_p. Germany has the most capacity, reaching 35.5 GW_p as shown in Figure 2. These figures should be compared with the theoretical portion of PV production relative to the total electricity demand by country, presented in Figure 3, to assess the impact on power generation. For instance, Italy ranks third in terms of installed capacity (17.6 GW_p) but has the highest share of PVs contributing to the electricity demand (7.8%).

Furthermore, the quasi totality of the cumulated installed PV systems in 2013 is grid connected. The expansion of PV installations is expected to continue in the near future, even though the development has begun to create some disturbances in the energy market, such as overproduction in the German market and the consequent negative energy prices (June 2013). The major problem expected will be due to the stochastic nature of the PV resource and its rapid growth, making it necessary to take measures to improve its integration into the electrical power system. The ultimate goal is the transformation of conventional stochastic PV sources in advanced systems with some degree of controllability, which can modify their output power depending on the grid conditions or system operator [8]. In particular, from the grid side, the objective is making PV systems participate in the frequency and voltage regulation through active and reactive power control (ancillary services) and to contribute to the fault ride-through capability improvement during faults (avoiding as much as possible the loss of generation capacity in case of a fault).

PV System Controllability Improvement

The controllability improvement of a PV system requires the modification of its control strategies to be able to control the active and reactive power injected in the point of common coupling with the grid. Reactive power services are relatively simple to provide for conventional PV systems as they are equipped with power electronic converters, which can easily control the

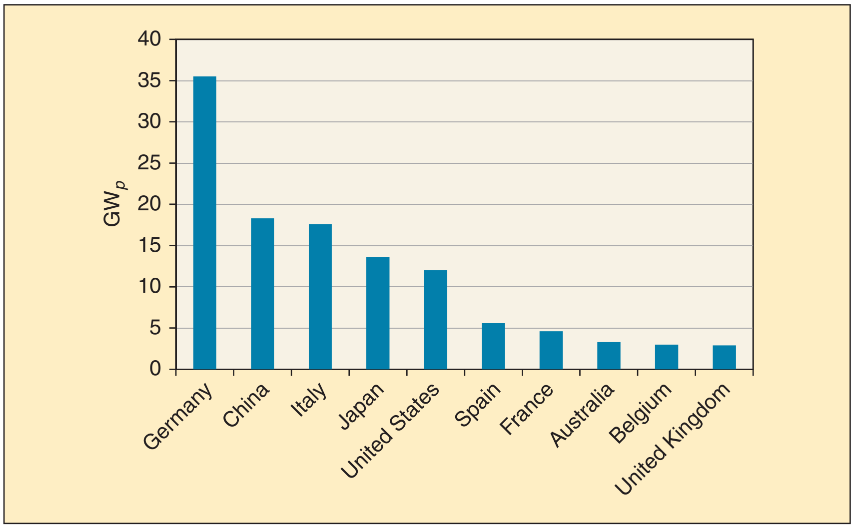

FIGURE 2 – The total installed capacity in the world by the top ten countries in 2013 [7].

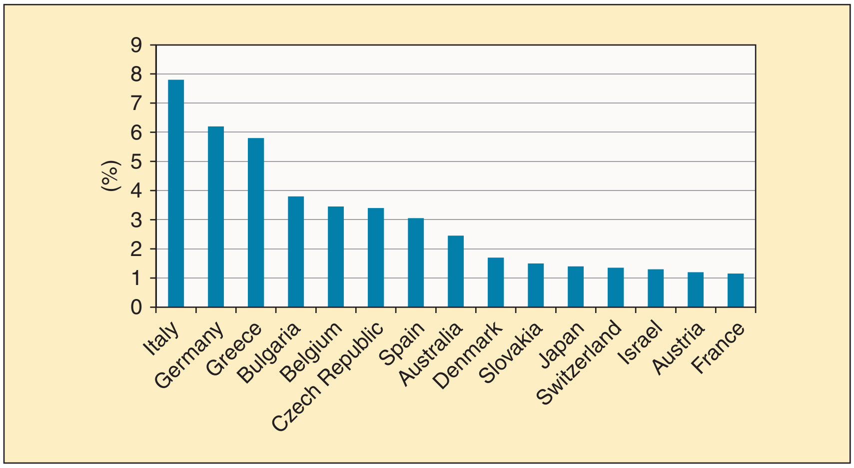

FIGURE 3 – The theoretical contribution of PV electricity production based on the installed capacity in 2013 [7].

amount of reactive power exchanged with the grid (obviously within the limits of the maximum apparent power of the converter). In contrast, the provision of active power services is not straightforward as conventional PV systems are operated with maximum power point tracking (MPPT) strategies [9] to maximize the produced energy. Consequently, there are two main possibilities for providing active power services: 1) the operation of the PV system in a nonoptimal operation point to reserve an active power margin for grid services or 2) including support technologies such as an energy storage system (ESS) as shown in Figure 4. The choice between both options is not obvious as it depends on economic factors (the regulatory frame, the price of energy, the price of ESS technologies, etc.) rather than technical ones.

Operation in a Nonoptimal Point

This solution requires the modification of the inverter's control strategies to make them work in a nonoptimal operation point (instead of following an MPPT reference). This is not obvious for an individual PV system as it is not obvious to calculate the instantaneous active power margin. However, in the case of various individually controlled systems, it is relatively simple as it is possible to operate one of them in MPPT mode and ask the rest of the PV systems to supply a fraction of the power generated by the MPPT-driven system (assuming that all the PV systems have a similar instantaneous radiation and, consequently, similar instantaneous power generation capacities). In this case, this function can be implemented by a central controller (CC), which will send references to all the PV systems to achieve the expected global operation. Depending on the communication capabilities between PV systems, some grid-control functions can be implemented at the PV inverters themselves (to act quickly without waiting for the references sent by the CC) and some others at the CC (which will generate the references for the PV inverters). In case of slow communications (hundred of milliseconds as in the case of most PV plants), fault ride-through capability functions should be implemented locally at each PV system level rather than at the CC level as they require a fast response. In contrast, active power/frequency control and reactive power/voltage control functions are implemented at the CC as they are intended to act in almost steady-state conditions.

Evidently, this solution means not injecting the maximum available PV energy and therefore a reduction in incomes, but in contrast, it does not require important additional investments for the PV system (only control algorithm modifications).

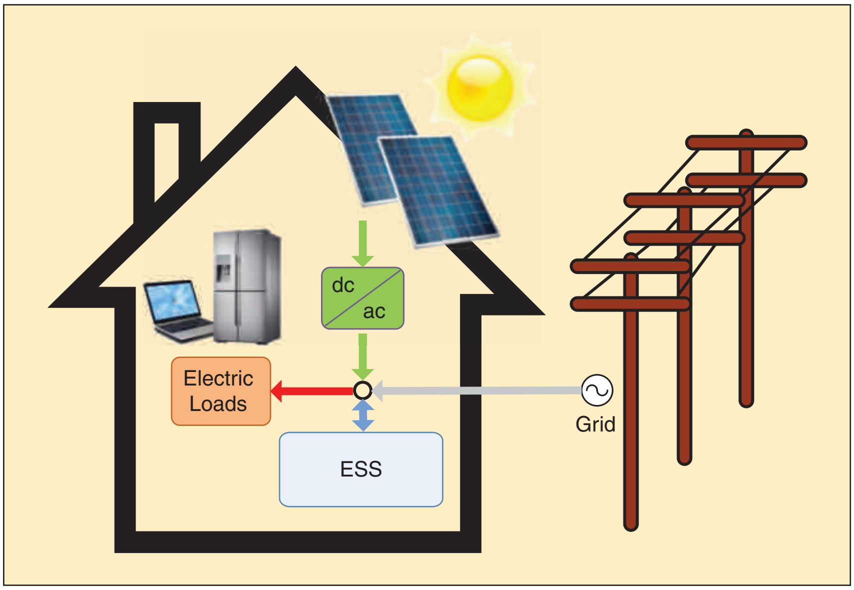

FIGURE 4 – The integration of PV technologies with an ESS.

PV System with an ESS

To avoid wasting PV energy, an alternative solution is to install an ESS at the dc or ac level of the PV system. In the case of several PV systems, a centralized (one big ESS as shown in Figure 5) or decentralized solution (many small ESSs) could be envisaged. This solution allows the PV systems to inject their maximum energy and respond to the grid requirements using the ESS. Evidently, this solution has a considerable investment cost as the size of the ESS can be relatively important.

The issue of installing ESSs with PV systems is not new as the first references date from the late 1980s [10].

Nevertheless, the lack of maturity of ESS technologies and the small rating and number of installed PV facilities at that time made this solution unfeasible. Then, in the early 2000s, with the boom of grid-connected renewable systems, the subject gained interest again with initiatives such as the European Network for the Investigation on Storage Technologies for Intermittent Renewable Energies (INVESTIRE) [11]. The main output of this project was a study on the contribution of ESSs to the integration of renewable energy sources (RESs) and some recommendations of research and development strategies for their improvement, but no industrial or large-scale demonstration facility was built. In recent years, the context has been rapidly changing mainly because of the significant development of PV systems as well as many of the ESS technologies [lithium-ion (Li-ion) and sodium–sulfur (NaS) batteries, ultracapacitors, etc.] and the increasing demand on the operating conditions of renewable generation systems. As a result, the possibility of implementing ESSs with PV systems is of particular relevance today. According to the German Economic Affairs and Energy Ministry's foreign trade and investment promotion agency, "A number of factors are coming together that will lead to a boom in PV energy storage solutions in Germany" [12]. Furthermore, the market research company EuPD expects sales of residential solar power storage systems to rise in Germany to 100,000 units in 2018, up from 6,000 in 2013 [13]. There is also an increasing interest in ESSs in big PV plants, confirmed by several demonstration projects such as the Innovative Lithium-Ion System project [14]. In this project, a 1-MW Li-ion battery was installed in a 1-MW PV power plant with the overall objective of reducing the cost of energy, providing ancillary services, improving network stability, and offering backup functions. The results of this project demonstrated the technical feasibility of the grid integration improvement of PV plants using ESS technologies.

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From an economical point of view, even if the price of ESSs is still very

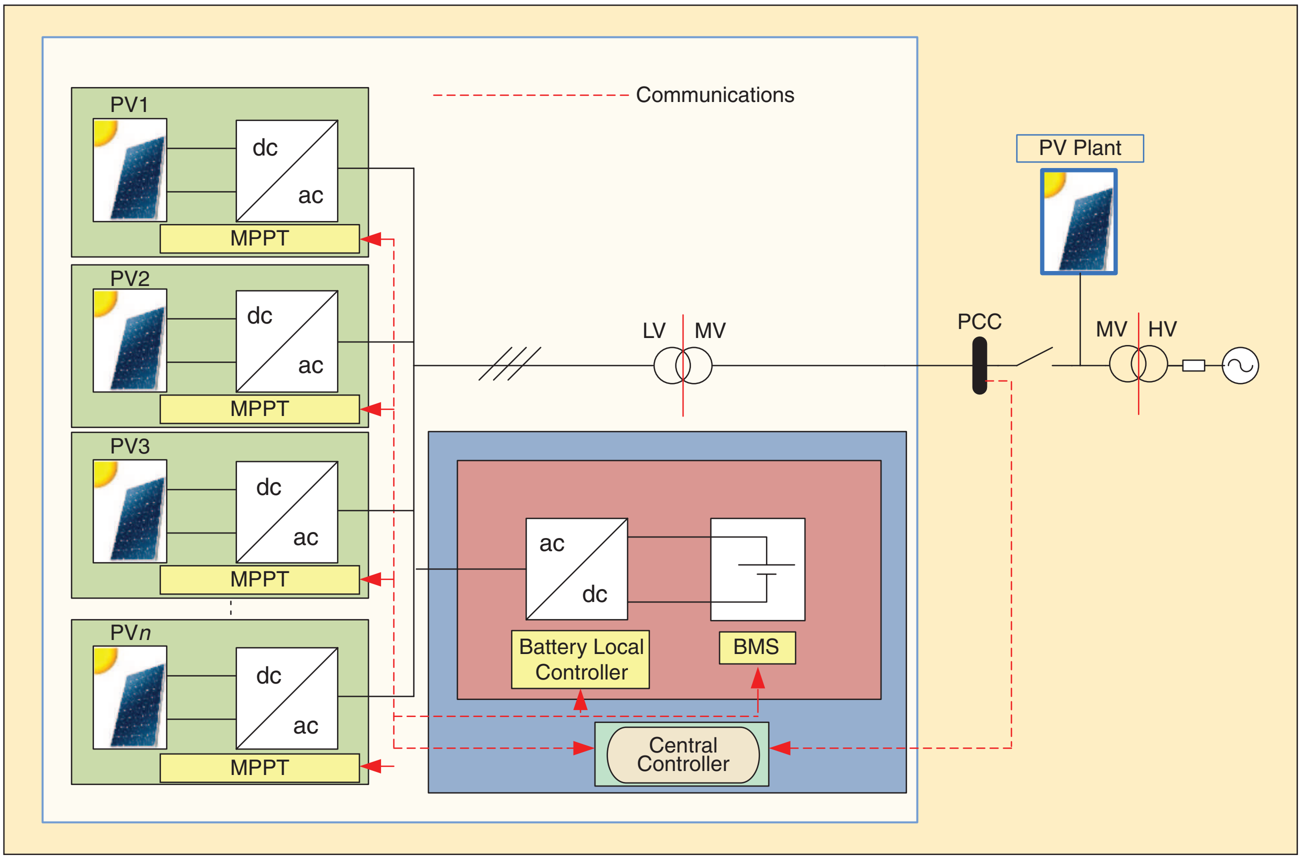

FIGURE 5 – A PV plant with an ESS.

Microgrids are considered the key building blocks of smart grids and, thus, are able to increase the system's flexibility, locally solving PQ problems and integrating DERs and storage systems.

high (around US$600/kWh for Li-ion [15]), there are some RES applications in which it can already be economically feasible or necessary. One example of this kind of application is islands in which grid-connection requirements are becoming very demanding for RES technologies. For instance, Puerto Rico, with an aggressive renewable portfolio standard target of 1.6 GW of RES installations by 2017, has released a document of minimum technical requirements that may force RES developers to include ESS technologies to reduce instabilities [16]. Another example is the project for installing a series of batteries in a PV plant on La Reunion island [17] or a battery system in a PV plant on Kauai island, Hawaii, [18].

Integration in Microgrids

The most sophisticated form of PV grid integration is the implementation of microgrids. In this kind of facility, PV systems are combined with other "loads and distributed energy resources (DERs) (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded" [19]. The combination of PV systems with other generation and storage technologies in microgrids is not new [20]. These applications have been generally oriented to remote locations such as telecomm systems, mines, and other commodity extraction facilities not connected to an existing grid; physical islands; rural villages; and mobile and tactical applications for military agencies. But now the challenge is to make it economically feasible in grid-connected applications as well. Several factors are pushing toward this evolution, including the decreasing costs of solar PVs, better batteries, the rising concern about storms, the relaxation of prohibitions against distributed generation (DG) operation during times of grid stress (including the ability to island from the larger utility grid during emergencies), and ancillary service market reforms [21]. Consequently, the microgrid market is currently moving from mostly demonstration projects into full-scale commercialization. Concerning management, microgrids necessarily include a management system, which will perform different functions depending on the state of the microgrid: when it is operating in parallel with the grid, the microgrid can operate as a self-consumption unit, exporting only the surplus energy production (with an almost zero energy balance with the grid); it can also support the grid stability (frequency and voltage) and optimize local energy resources (fuel, PVs, and wind). In the case of islanding, for example, due to a grid voltage failure, the microgrid can continue feeding the loads isolated from the grid, and therefore, its main function will be to control the local voltage and frequency parameters.

Energy Management Aspects

General Aspects

As solar energy is a fluctuating resource, a major challenge is meeting this intermittent energy production with dynamic power demand. EMSs can address this issue by using energy storage technologies, but expensive investment costs and short lifetimes are currently the principal barriers to their development. The optimization of the energy storage usage and operating costs considering the strong operation constraints has been the subject of several studies [22].

The Various Control Levels

The EMS is composed of a supervisor, which carries out the optimization process to realize the optimal power flow between the elements of the system. The supervisor is able to generate control signals after having completed the three-stage process, as shown in Figure 6. The first layer provides the forecasts of the necessary inputs for the optimization process. These mainly concern weather conditions (irradiance and temperature), power production, load consumption, storage availability (state of charge and state of health), and the main grid energy prices.

During the second stage, the optimization problem is solved while respecting the physical constraints in the microgrid and the ESS. The solution produced aims to establish the state of each equipment while reducing the energy bill of the storage owner. Optionally, corrections to the forecast of the input variable may be carried out beforehand.

In the last stage, the local control stage is in charge of generating control signals to the power electronic devices, which should be applied as reference values at a given time schedule [24].

PQ Requirements

Microgrids are considered the key building blocks of smart grids and, thus, are able to increase the system's flexibility, locally solving PQ problems and integrating DERs and storage systems. The recent introduction of DG, particularly PV systems, has raised new issues regarding PQ [25].

PQ has several known definitions and related standards; however, it can simply be seen as a measure of an ideal electrical system [26]. The IEEE defines PQ as "the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment" [27], while the International Electrotechnical Commission (IEC) defines it as "characteristics of the electric current, voltage, and frequencies at a given point in an electric power system, evaluated against a set of reference technical parameters" [28].

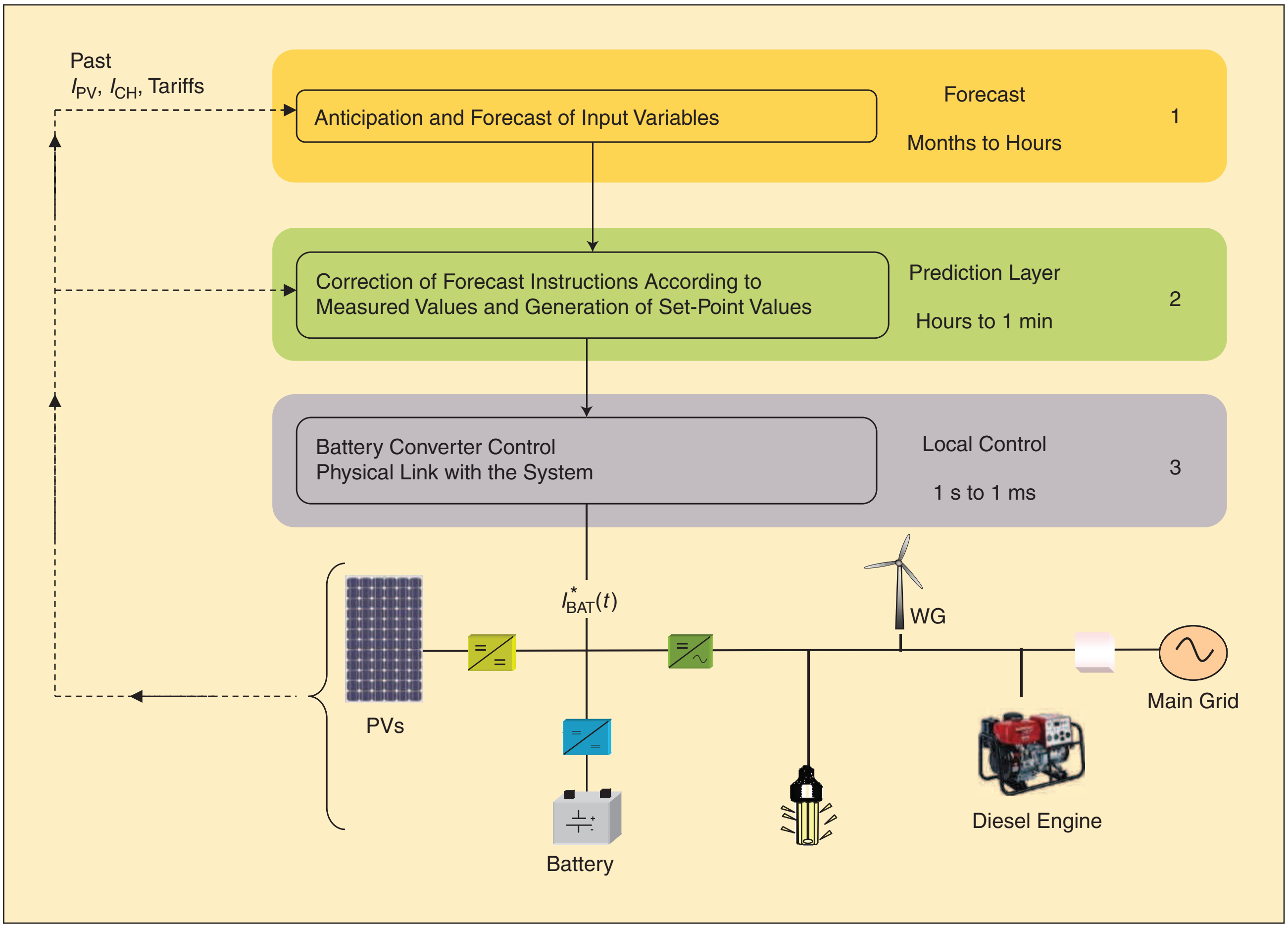

FIGURE 6 – The power flow optimization [23].

Although there are no specific IEEE or IEC standards regarding isolated electrical systems, PQ issues should be similar to interconnected systems. There are several standards related to PQ and DG integration. As an example, one could refer the following standards:

- IEEE 1159 provides a detailed description of PQ variations and the recommended monitoring practices [29].
- IEC 60038 defines the set of standard voltages used in low- and high-voltage ac grids [30].
- IEEE 1547 provides specifications for grid connecting of DG and ESSs [31].
- IEC 61727 defines the characteristics of the utility interface regarding PV systems [32]. When the PV inverter is grid connected, these standards (summarized in Table 1) must be followed.

TABLE 1 – A SUMMARY OF THE MOST IMPORTANT PV-RELATED STANDARDS.

	IEC 61727		IEEE 1547	
SUPPLY VOLTAGE LEVEL FOR NORMAL OPERATION	**VOLTAGE RANGE (V)**	**DISCONNECTION TIME (s)**	**VOLTAGE RANGE (V)**	**DISCONNECTION TIME (s)**
	196–253	**0.16**	**97–121**	**0.05**
Frequency deviations for normal operation	50 ± 1 Hz		59.3 < f < 60.5 Hz	
Total harmonic distortion	5%		5%	
Power factor	More than 0.9 (lagging) for 50% of rated power			
DC offset	Less than 1% of the rated root-mean-square (RMS) current		Less than 0.5% of the rated RMS current	

Microgrids are the key building blocks of smart grids; they aim to enable the implementation of several operative functions, particularly in the PQ domain. Among the smart grid operative functions, one can consider voltage unbalance compensation [33], harmonics suppression [34], or sensitive load buses mitigation [35]. Some authors suggest the use of a power electronic conditioner, connecting the microgrid with the utility grid, to mitigate the aforementioned issues such as voltage sag and swell, voltage interruption, harmonics, and reactive power in both interconnected and islanding mode [36], [37]. This power electronic conditioner should be similar to a unified PQ conditioner or a unified power flow controller, implementing the following control scheme: 1) control the shunt converter in voltage mode (to produce a well-regulated voltage in the microgrid), 2) control the series converter

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in current mode (to produce a balanced sinusoidal line current), and 3) control the series converter as a large impedance (thus limiting the line current during utility voltage sags).

Protections

Most national and international grid codes, which regulate the PV production systems connected to the grid, provide basic guidelines regarding the integration of those systems. Considerable efforts have been made; however, high levels of penetration can bring operating problems regarding system protection. In the case of a fault, several PV-related problems could occur. For example, after the utility protective device opens, the PV DG can still feed the fault on the adjacent feeders [38]. Also, the protection coordination, along with the loss of speed in protective devices and unintentional islanding, is a major problem [39]. Better communication systems will help to mitigate this problem [40]. On the other hand, there is a need to rearrange the protective devices' settings whenever new PV DG systems are introduced into the microgrid [41]. If the PV system can supply enough current into a fault, the protective device will not see the fault at all, which may also lead to coordination loss between the protective devices. A recurrent problem is to establish how many small PV systems should be considered to readjust the protection settings. Problems such as sensitivity and selectivity loss, auto-reclosing, and unintentional islanding could be minimized. Grid designers and operators must ensure a minimum safety margin to operate the grid reliably under abnormal conditions.

As mentioned before, the grid connection of PV systems-related standards addresses the problem of islanding detection when a fault occurs, considering a PV system disconnection within 2 s. When the main grid power returns to stable conditions, reconnection could be initiated, provided that a prior grid synchronization exists [31]. Particular attention should be paid to the timing and effects of reclosers if they exist on the main grid's feeder to which the microgrid reconnects. A complete list of anti-islanding protection strategies (local, either passive, active, or hybrid; or remote, based on communication) is given in [42].

National and international grid regulations require maximum/minimum voltage and frequency protections to be installed in PV systems connected to the grid. The cloud dependency of the PV system's produced energy can affect the grid voltage profile, particularly in microgrids. Additionally, the intermittent PV voltage protection nature will lead to supplied energy reduction, less revenue, and increased PQ problems [43]. Since microgrids present high line resistance/reactance ratios, they are quite sensitive to active power deviations. Although PV systems are part of the problem, they can also be part of the solution; thus, they can help mitigate this problem by providing fast active-power PV control [44].

The impact of several DG units was the basic reason for utilities to impose strict regulations to maintain the operation's safe limits along with the grid's stability and security. One major regulatory problem is related to the specific load conditions, leading to specific load requirements, as is the case in Spain and Italy. This lack of regulatory harmonization has increased research, testing, and documentation efforts, along with more complex PV power inverters (i.e., a higher number of parameters and parameter settings). The European Network of Transmission System Operators for Electricity (ENTSO-E) is playing an important role in harmonizing the requirements in different countries [45].

As mentioned before, most of the utilities do not allow islanding operations [46]. However, some of them allow intentional islanding of user facilities, isolating some private installation from the main grid, and thus improving the local PQ operation [47]. This can only be achieved if the available DG devices are available to support local loads, providing suitable protection devices and coordination with the utility grid. This concept was already successfully tested in the laboratory considering a PV generator, battery storage, loads, and a grid-controlled connection [48]. IEEE Standard 1547 addresses the islanding problem, imposing that the distributed resource should detect the island condition and disconnect within 2 s. However, IEEE P1547.4, *Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems,* addresses the issue of microgrids and intentional islands that contain distributed resources connected at a facility level and with the local utility [49], [50].

Economical Issues

The share of renewable energy production in the energy production mix is expected to grow from 10% in 2009 to 23% in 2035, with wind power and solar PVs being key technologies for this growth [51]. Despite economic, policy, and industry turbulence, the growth of renewable power technologies continued in 2012 and 2013. In 2012, solar PV capacity grew by an estimated 42% (29–30 GW) compared with the 2011 cumulative levels. Solar PVs has entered a phase of deeper consolidation, particularly among smaller and higher-cost manufacturers, driving the reduction of technological capital costs. In 2012, large-scale systems' capital costs were at US$1,500–3,500/kW and small-scale systems were at US$2,400–6,000/kW [52]. The small-scale solar PV systems are still expensive, but microgrid and off-grid applications are already competitive with other technological choices. Grid-connected residential PV systems can achieve lower generation costs than retail electricity prices for households in countries with good solar resources and high retail prices. In a microgrid context, prices are lowering toward US$2,000/kW for the small-scale systems and toward US$1,200/kW for the large-scale systems. PV panels count for 50% of the total system cost, while power inverters and mounting structures count for 15 and 10%, respectively. Regardless of these variable costs, an average US$1,200 in fixed costs should be considered, mainly for metering, commercial support, and grid connection.

Recent studies have indicated that solar PVs (along with other RESs) could contribute to the full elimination of fossil fuel consumption [53]. The increasing importance of power electronics has also been realized for energy savings [54]. However, for microgrid-connected PV systems to play their role toward 2020's environmental targets, reliability is a key issue. Historically, inverters have been one of the least reliable components in solar PV production systems; due to harsh environmental conditions, a tremendous amount of stress is placed on these electronic devices [55]. Power inverter manufacturers must adapt their products to extreme climatic conditions [56], [57]. In a PV inverter, a high operating temperature at the junction of an inverter switch is the key factor in decreasing the mean time between failures [58].

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Electrical efficiency improvement is also a major issue in all PV systems. To enhance the overall efficiency, thus improving the economic value of PV systems, MPPT plays an important role as the trackers are capable of extracting nearly the maximum available power from the PV arrays. However, MPPT schemes must take into account several other issues, such as the power converter itself, the adopted structure (centralized or decentralized), simplicity, and weather conditions. To achieve a faster response as well as minimum steady-state oscillations, adaptive step-size tracking schemes are usually recommended [59]. Also, digital MPPT schemes have been adopted since they are more flexible, allowing for improved efficiency and reliability [60], [61].

In recent years, investors have been looking at solar PVs as a large potential technology in the global energy market. Higher penetration percentages will decrease the break-even cost [62]. On the other hand, renewable resources located near electric loads (such as in microgrids) have the further potential benefits of reducing electrical losses, minimizing transmission costs, and avoiding expensive transmission expansion projects [63]. Thus, an economical design of solar PV systems must be taken into consideration [64].

Rural Microgrids

Rural microgrids are present in electrically isolated regions of the world, providing steady community-level electricity service for local populations. Typically, the total installed power reaches 100 kW, with less than 1,000-V levels and single or three phases. Such networks provide village electrification while offering the possibility for future main-grid connection. They combine RESs (wind and

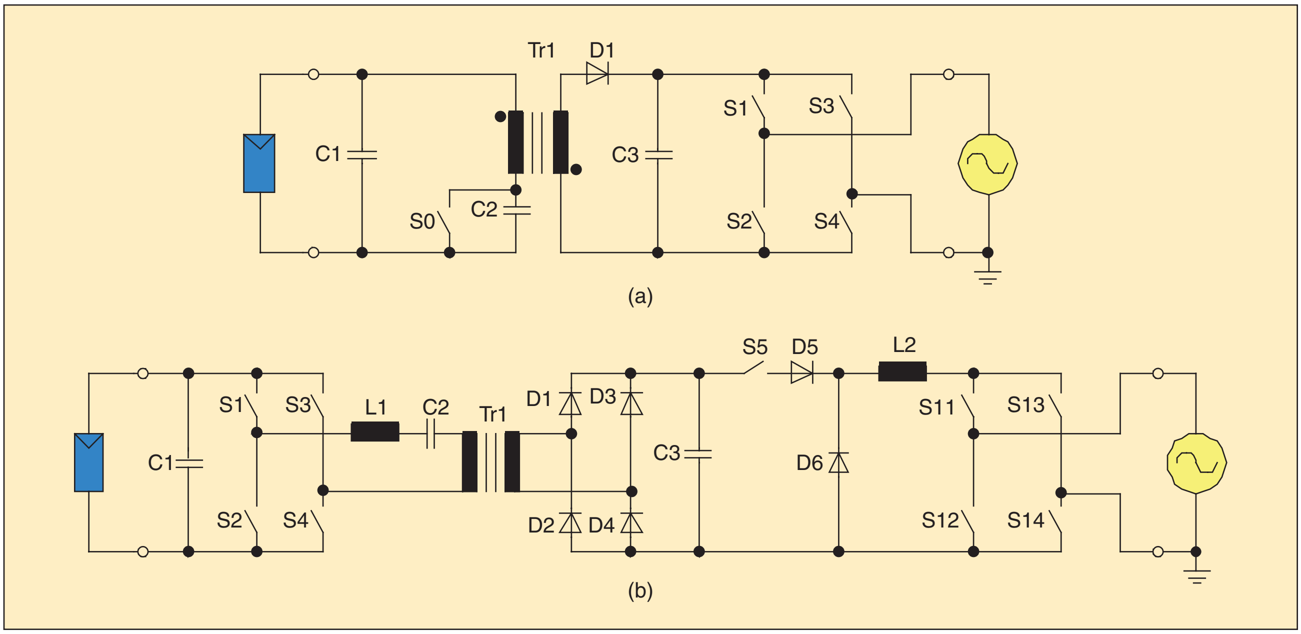

FIGURE 7 – The basic circuits of microinverters: (a) a resonant flyback converter with an unfold stage [70] and (b) a resonant full bridge converter with a buck converter and unfold stage [71].

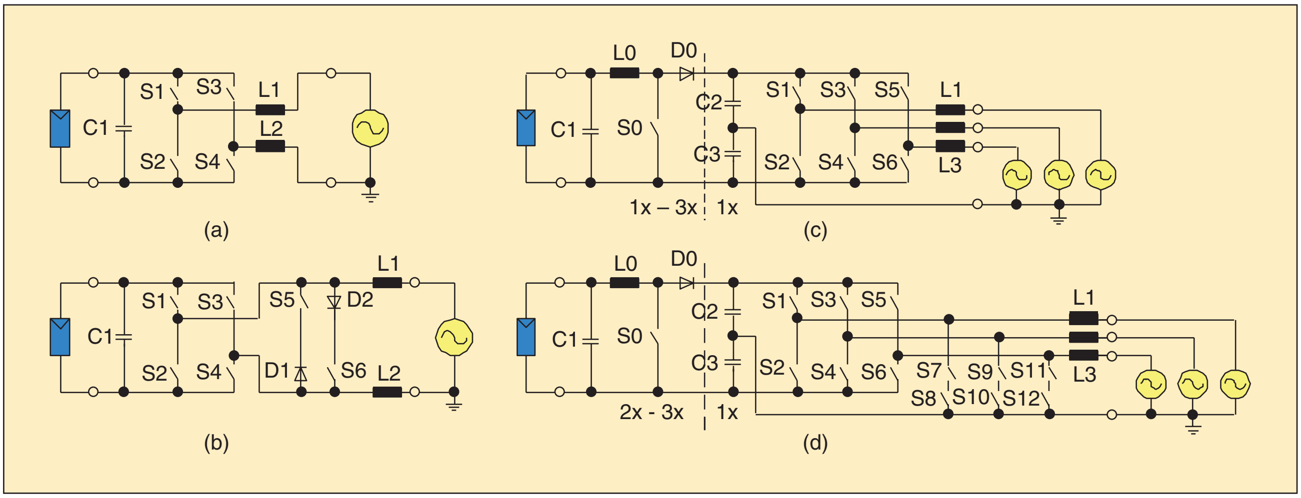

FIGURE 8 – The basic circuits of single- and three-phase string inverters: (a) an H4-bridge, (b) an HERIC topology [70], (c) a B6 bridge with a booster, and (d) a three-phase transistor clamped [73] with a booster.

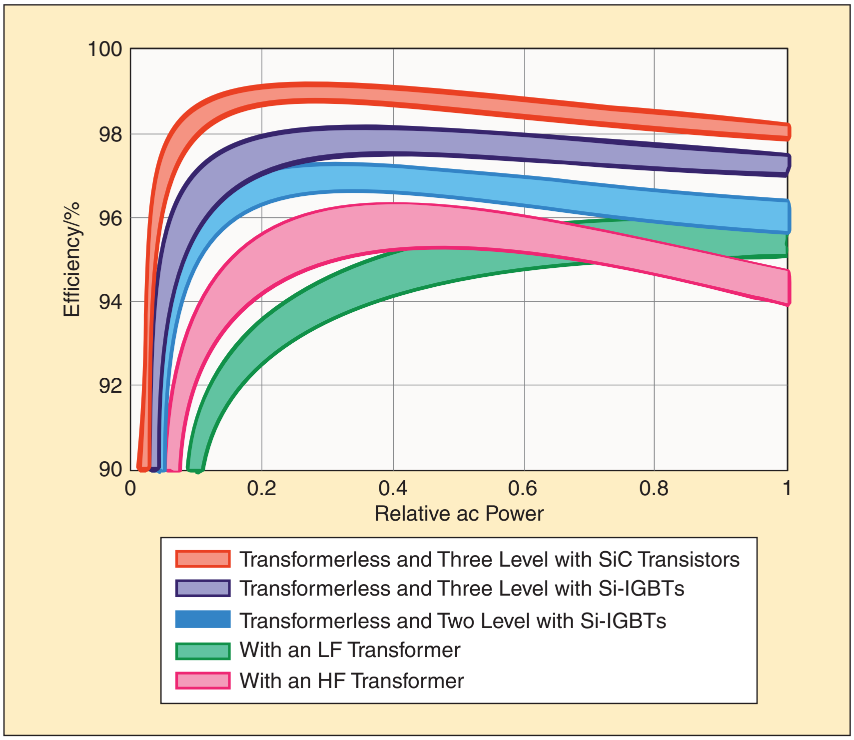

FIGURE 9 – The efficiency curves of string inverters.

PVs) and backup generation supplied by fossil fuels. PVs are extensively used in microgrids because the solar energy technology can ensure a limited daily energy allowance, it is low maintenance and easy to install, and it can supply extra energy under certain weather conditions. Some challenges for rural microgrid operation are mainly linked to the total impact in case of failure and maintenance needed in case of problems.

In rural microgrids, lower investments are needed when compared to individual power plants since costs are mutualized. The current critical issues concern the ownership and management schemes, load management, invoicing and tariffs for consumers, future expandability, and connection. In the current rural projects running in Africa, consumers pay a monthly fee, enabling daily energy allowance access. Automatic load management tools may also be used to share the available energy and guarantee the supply of critical loads [65].

Associations of Clusters: Smart Cities and Neighborhoods

In an urban environment, the association of several microgrids can be applied to larger clusters such as smart neighborhoods, smart communities, and smart cities. Smart cities are able to make intelligent responses to various kinds of needs in daily life, such as environmental welfare, public safety and city services, and industrial and commercial activities for its citizens [66]. In the energy sector, the smart grid concept integrates benefits from information and communication technology to "intelligently integrate the actions of all users connected to it—generators, consumers, and those that do both—in order to efficiently deliver sustainable, economic, and secure electricity supplies" [67]. The GreenLys pilot project, taking place in the cities of Lyon and Grenoble in France, illustrates the smart grid by finding the optimal energy management strategies in an urban low-voltage grid, with high penetration rates of DER units, EVs, and energy boxes for load management (smart buildings) [68].

One of the core components for realizing energy flow management, both in large-scale clusters as in microgrids, is power electronic devices, which are located at the interface of the grid, DER, EV, and smart buildings.

Microgrid-Dedicated Power Electronics Converters

Topologies of PV Inverters

Microinverters

Microinverters [69] are small PV inverters with a power range of 250–300 W and an input voltage of 30–40 V. Each microinverter is directly coupled to a single module. The parallel connection of systems with several modules and inverters is done on the ac side. Since the power level of microinverters is quite small, mainly single-phase inverter circuits are used. Figure 7 shows the typical circuits of microinverters. The circuit in Figure 7(a) uses a resonant flyback converter that is rectified sinusoid modulated and an unfold stage, while the circuit in Figure 7(b) uses a resonant full-bridge converter, a sinusoid-modulated buck converter, and an unfold stage. Both circuits are unable to deliver reactive power because of the unfold stage and the diodes D1 and D5, respectively, which do not allow a bidirectional power flow. Therefore, today's microinverters are not well suited for use in microgrids. New microinverters should be capable of four-quadrant operation to meet the requirements of microgrids as well as the new requirements of public grids.

String and Mini Central Inverters

String and mini central inverters are designed for residential systems in the power range of 3–30 kW and a connection to the low-voltage grid. The maximum dc input voltage is in the range of 500–1,000 V. Single-phase inverters mainly use an H4 bridge or a highly efficient and reliable inverter concept (HERIC) topology (shown in Figure 8). Because of the high-input voltage, single-stage circuits without boosters are possible. Three-phase inverters typically use a booster since they need double the dc link voltage of single-phase inverters. Three-level circuits, such as HERIC or neutral point clamped (NPC) topologies, offer several advantages such as higher efficiency, lower cooling requirements, higher switching frequencies, and smaller inductors. All inverters are able to provide reactive power, and most inverters are also certified according to the low-voltage ride-through (LVRT) tests. Therefore, they are well suited to the requirements of microgrids.

Figure 9 shows the typical efficiency curves of different inverter types.

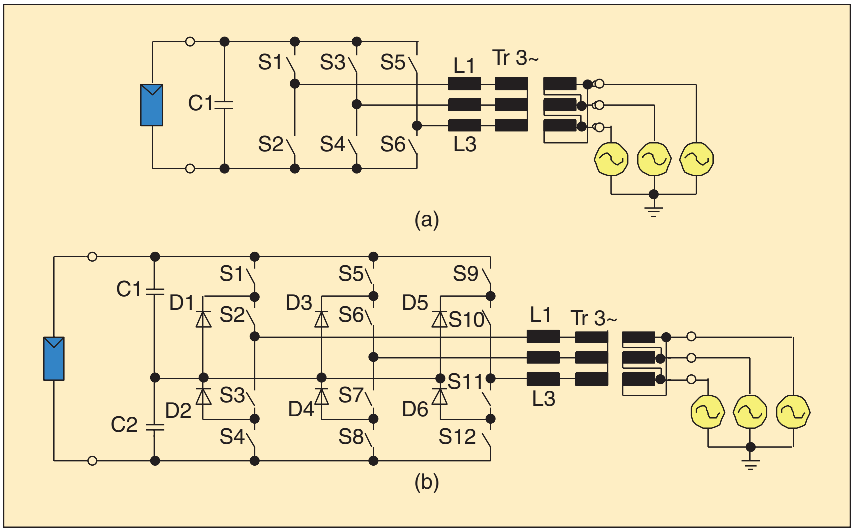

FIGURE 10 – The circuits of central inverters: (a) a B-6 bridge and (b) a three-phase neutral NPC [60].

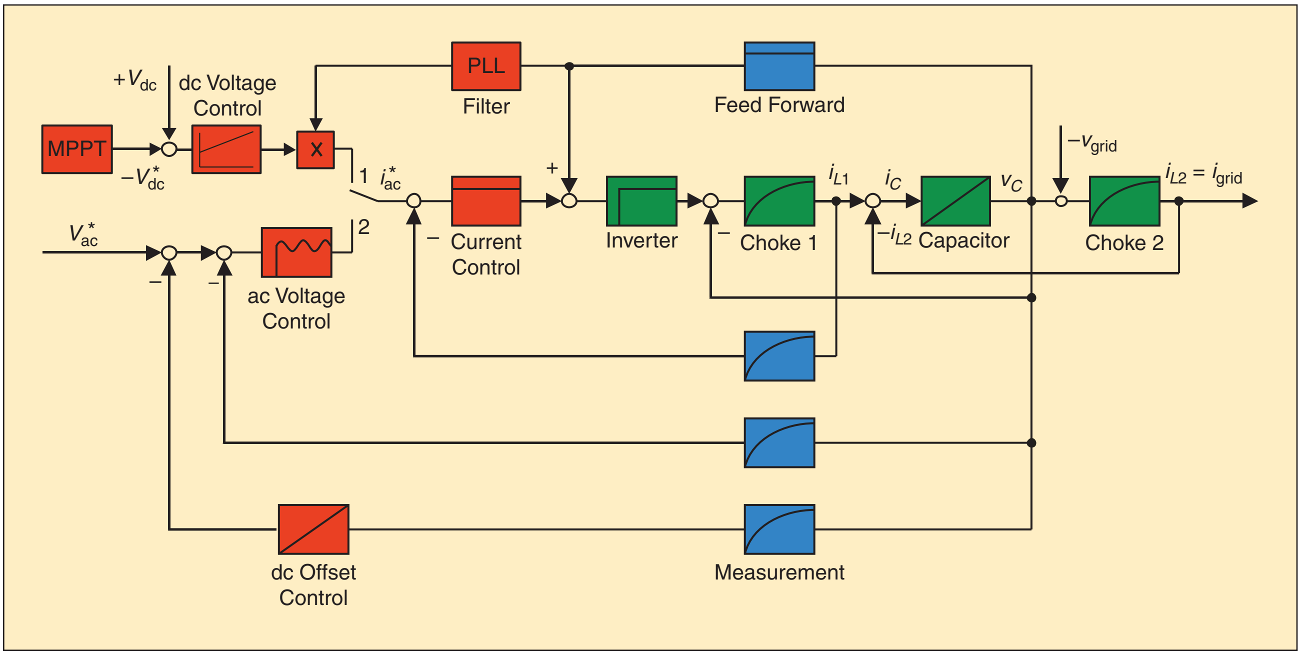

FIGURE 11 – The basic control scheme of a single-phase inverter for grid-connected operation (switch position 1) and island operation (switch position 2). The scheme shows the characteristics of the inverter hardware (green), the measurement devices (blue), and the cascaded controllers (red).

The highest efficiencies of up to 99% [74] are achieved with three-level circuits and silicon carbide (SiC) semiconductors. Inverters with low-frequency (LF) or high-frequency (HF) transformers for galvanic isolation have the lowest efficiencies.

Central Inverters

Central inverters are designed for powers of 100 kW up to the megawatt range. They are typically connected to the medium-voltage grid. Since they use their own medium-voltage transformers, the voltage on the low-voltage side can be chosen according to the requirements of the inverters and the PV generators. Typical ac voltages are in the range of 270–350 V to avoid the need for dc boosters. Figure 10 shows two typical circuits of central inverters. Three-level circuits are advantageous concerning the efficiency and size of the main inductors. Central inverters are able to deliver reactive power and limit their power according to the requests of the grid operator. They also fulfill the requirements of the LVRT tests. Therefore, they are well suited to the needs of microgrids.

Control of Inverters for Microgrids

There are two basic control methods for inverters: cascaded control and state-space control. Additionally, there is the possibility to control the original values or to transform the three-phase voltages and currents with the Clarke transformation (3-2 transformation) in the α, β coordinates or to use the Park transformation (d, q transformation) to get dc values in a rotating coordinate system. If not all signals can be measured, a state observer can calculate the missing values. Figure 11 shows the basic control scheme of a single-phase inverter that also can be used three times for a three-phase inverter. The green blocks show the characteristics of the power electronics hardware, and the blue blocks show the measurement devices for measuring the inductor current, the filter capacitor voltage, and the dc offset in the filter capacitor voltage. The red blocks show the controller parts of the cascaded control scheme.

If the switch is in position 1, the inverter works as a current source for grid feed-in. The MPPT calculates the set point for the dc voltage. A proportional-integral controller controls the dc voltage. Since the output of the dc voltage controller is a dc set point for the RMS value of the ac, it has to be multiplied with the normalized and filtered ac voltage to get an ac set point. The current controller should be rather fast, so a P-controller is a good and simple solution.

If the switch is in position 2, the inverter works as a voltage source for the island mode. The sinusoidal set point for the voltage is calculated with the microcontroller or digital signal processor. A special dc offset controller controls the dc offset of the ac voltage to zero. For the ac voltage control, a generalized integrator [75] can be used, which controls the RMS value of the ac voltage. If several inverters are connected in parallel in an islanding microgrid, additional droop controllers can be used to calculate the set points of the ac voltage and frequency [76].

Grid Codes

The interest in building microgrids is so new and has such a big impact on the power system that regulatory issues have yet to fully catch up. A good example of this is what is currently happening in the United States. After the devastating effects of Superstorm Sandy, Hurricane Irene, and Tropical Storm Lee, there is a clear interest to improve the reliability and resilience of the power system, in which microgrids play a fundamental role. In Connecticut, for instance, officials announced in August 2013 that US$18 million would be used to fund nine microgrid projects to support local distributed energy generation for critical facilities [77]. The New York State 2100 Commission released a preliminary report in January 2013, in which it suggested ways to make the state's infrastructure less vulnerable to severe weather, including microgrids as part of its vision for the state's future power infrastructure [78].

However, the regulations are currently unclear. Currently, most advanced distribution interconnection rules generally recognize three types of generation interconnections: net metering, self-generation (nonexport), and complete energy export. None of these types fit completely with microgrids, which require both grid-connected and island-mode operations.

The primary issues to be solved by regulations are the safety and reliability of microgrids, but other aspects must also be dealt with, such as the definition and management of the connection to the distribution and transmission systems, financial and tariff issues, and ownership concerns [79]. This is probably the main challenge that microgrids are facing currently, as it is also directly linked to their business model and, consequently, the profitability of such facilities and may become their biggest hurdle [80].

The situation in Europe, and particularly in Germany (the country with the most advanced regulations for nonconventional generation systems), is very similar as grid codes for public grids [76], [81], [82] are currently not well suited for the requirements of microgrids.

Conclusion

Microgrids integrating PV production will certainly play a large role in the future grid. The decreasing costs of PV technologies, the reliability and flexibility of power electronics, and the progress of ICTs are encouraging in this direction.

Once the conditions of large deployment are assessed, one has to take into consideration the rise of intelligent buildings and plug-in hybrid vehicles. These two systems will not only increase the complexity of energy flow management but will also offer very interesting degrees of freedom. However, the remaining problem of regulation and coordination with distribution and transmission system operators has yet to be addressed.

Biographies

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