Chapter 3
An Overview on Distributed Generation and Smart Grid Concepts and Technologies

Concettina Buccella[1], Carlo Cecati[1] and Haitham Abu-Rub[2]

[1] *Department of Information Engineering, Computer Science and Mathematics, University of L'Aquila, and DigiPower Ltd. L'Aquila, Italy*

[2] *Electrical and Computer Engineering, Texas A&M University at Qatar, Doha, Qatar*

3.1 Introduction

The existing power grid can be considered as a hierarchical system where power plants are at the top of the chain and loads are at the bottom, resulting in a unidirectional electrical pipeline managed with limited information about the exchange among sources and end points.

This situation has severe drawbacks, including the following:

- The system is sensitive to voltage and frequency instabilities as well as to power security issues caused by load variations and dynamic network reconfigurations.

- The implementation of demand side management strategies, which would be very useful for reducing the risk of failures and blackouts and for increasing system efficiency, is not allowed, moreover.
- It is not suitable for the integration of renewable energy.

During the last decade, the electrical energy market has been characterized by a growing demand for energy and two important innovations: the quick growth and massive diffusion of renewable energy systems (RESs) and the subsequent rapid development of distributed generation (DG) systems and smart grids (SGs) [1–5]. Conventional unidirectional power systems consisting of few very high-power generators producing hundreds of megavolt-amperes and connected with substations through transmission lines and feeding distribution systems supplying loads through a tree are being replaced by wide, complex, and heterogeneous meshes, embedding a huge number of loads and generators, the latter supplied by different sources (fossil, nuclear, gas, wind, sunlight, biomass, etc.) and operating at different power levels (from a few kilovolt-amperes up to hundreds of megavolt-amperes) and voltages, each with its own characteristics (e.g., electrical, mechanical, thermal, photovoltaic (PV) surface) and dynamics.

According to many analyses, future electrical systems should have the following parameters [6–12]:

- High power capability: with the increasing demand for energy in industrial, residential and civil applications and the incoming large-scale diffusion of electric vehicles, electricity is becoming the main power source of the modern world and hence the need for it will increase significantly during the next years; this trend is expected to remain positive for many decades and will be marginally influenced by external perturbations such as economic or political crises.
- High power quality and reliability: electricity must be available whenever it is needed with the lowest or no latency, stable voltage and frequency and low harmonic distortion.
- High efficiency: electricity should not be dispersed during production, transportation and distribution processes; the grid and the loads should be managed to achieve maximum system efficiency.
- High flexibility: the power system should be highly configurable and should allow smooth integration among different power

sources; moreover, dynamic changes of loads and power sources should not influence power quality.

- Low environmental impact (i.e., sustainability): renewable energy sources should progressively replace traditional sources; moreover, even in the short term they should be fully integrated into the existing power system.

Previous requirements cannot be satisfied by traditional power systems; therefore, during the next years a huge revision of the present systems is expected with the introduction of many new functions, systems and modus operandi, commonly referred to as the distributed generation (DG) and smart grid (SG) revolution. This is changing the way in which next-generation power systems have to be designed, operated and maintained, and can be achieved only by introducing new technologies, functionalities and operational approaches, which are as follows [13–18]:

- full exploitation of all renewables
- technological enhancements and large-scale diffusion of energy storage systems
- massive introduction of Information and Communication Technologies (ICTs)
- implementation of high-granularity self-healing and resiliency against unwanted

situations, such as blackouts or natural disasters

- consumers' active participation to the electricity market
- introduction of new products, services and markets.

With reference to the last point, the same ICT infrastructure could be shared among different services (water, gas, electricity, heat, etc.) or different service providers. This should allow the hardware (HW) and software (SW) resource optimization necessary to sustain large investments in the realization of the communication infrastructure.

The following sections give an overview of the main technologies, features and problems of DG and SGs. Due to the breadth of topics, this chapter gives a short but comprehensive overview of these emerging topics.

3.2 Requirements of Distributed Generation Systems and Smart Grids

In order to fully satisfy energy demand, conventional power systems are operated taking into account the predicted power needs, thus producing a corresponding quantity of high-quality energy, that is, with stable output voltage and frequency. Because of the high thermal inertia of steam generators, peak demands are satisfied by producing amounts of electrical energy close to peak values, and hence significant energy surpluses are often available during periods of light load operations. When possible, the energy surplus is employed to increase the quantity of stored energy, typically in hydroelectric reserves.

However, the massive introduction of renewable energies does not solve the last problem and introduces several additional problems, mainly related to the fluctuating quantity and quality of the energy injected in the grid. Hence, in general, power system stability deteriorates instead of improving.

With this situation, intelligent management of produced and absorbed energy, together with the introduction of small-to-medium fully controllable generators, for example, turbo gas (TG) and combined heat and power (CHP) systems, which, being fully operative within few minutes or seconds, can be activated and deactivated according to short-term predictions, represents a viable if not unique short-term to medium-term solution.

In fact, at the current stage of technologies, energy storage systems, except hydro power plants, are unable to store and release the amount of energy often needed to satisfy peak demands, while static compensators (STATCOMs) and other high-power electronic devices, even if they are efficient under some kinds of transient disturbances, could be insufficient to guarantee stability in the case of large and long-term variations of electrical quantities. In addition, some types of energies such as nuclear or fossil are becoming critical either because of their impact on health and the environment or because they are potentially dangerous.

Another fundamental issue motivating the diffusion of SG is that the increasing demand for energy requires permanent enhancements or a redesign of transmission lines, and thus requires huge investments at national and international levels. Hence, several countries are changing their energy policies in favor of full exploitation of DG, the combination of RESs and clean traditional sources, improvement of existing power plants and user awareness about saving energy [19].

The new power systems will include a huge number of power lines often operating at different power and voltage levels, connected through intelligent routing nodes and capable of sustaining, monitoring, controlling and billing energy in a fully bidirectional power flow environment.

Other key elements of modern power systems are the electronic static converters necessary for the connection of RESs to the grid and storage systems, which is necessary to reduce the effects of energy fluctuations and power losses along lines. Their operations ensure power quality enhancements [20].

In short, DG and SGs are very complex systems requiring many technologies including, but not limited to, power systems, power electronics, communications, computer science, computational intelligence and so on, which are necessary for full and optimized integration among generators, loads and lines [21].

Moreover, tools based on previous technologies are necessary for improving overall energy management according to economic criteria and for creating sensibility among users concerning the rational use of energy.

At the current state of technology, the most diffused RES generators are PV, wind and hydro generators. Other possible sources suitable for DG are CHP systems, combustion motors, geothermal systems and fuel cells (Figure 3.1).

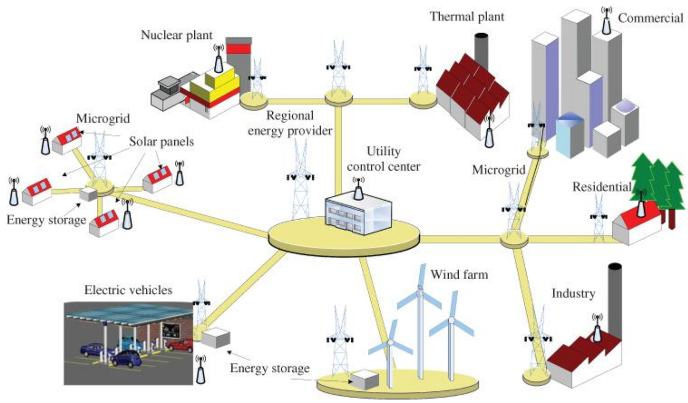

Figure 3.1 Smart grid architecture

3.3 Photovoltaic Generators

PV cells are direct current (DC) generators. Their voltage level depends on the intrinsic cell characteristics, the number of cascaded cells and their temperature. The available current depends on cell characteristics, the number of parallel strings (a string is a group of cascaded cells) and sunlight intensity. With present technology, they are arranged in panels providing up to 220–250 W at a voltage rating of 48–60 V. In fact, typical panels do not exceed 1.5–2 m^2 due to the need for easy handling. New technologies are emerging that improve PV energy conversion by means of cell efficiency enhancement and/or optical concentrators capable of increasing the quantity of energy applied to the cell surface [22]. This solution increases the power produced per surface unit but at the cost of very high temperatures, and hence suitable heat transfer systems are needed to maintain safe and efficient operations. Currently, some experimental systems propose to combine electricity and heat production (Figure 3.2).

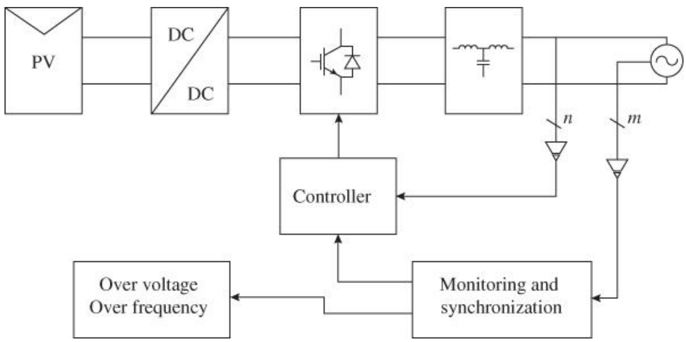

Figure 3.2 Schematic diagram of a photovoltaic system

In order to supply standard loads operating with alternating current (AC) – AC motors, lamps, air conditioners, electronic equipment, domestic and industrial loads and so on – panels are connected in series and/or in parallel, thus reaching the desired level of voltage and current; hence they supply an inverter [23–24]. The latter has to guarantee a stable and standard output (e.g., 400 V, 50 Hz), high conversion efficiency, grid synchronization (in the case of grid-connected systems), low voltage and current distortion and low cost. Moreover, it might be in charge of power factor control and harmonic mitigation. Usually, inverter operations are based on feedback control and two-level pulse width modulation (PWM); moreover, they are connected with the grid through suitable passive output filters.

A common solution includes inductive/ capacitive filter (LC or LCL) configuration. In order to maximize the extracted energy and to adapt the output voltage amplitude to the required level, a DC/DC converter with maximum power point tracking (MPPT) capability is usually interposed between cells and the single-phase or three-phase inverter. In grid-connected systems, a further requirement for the converter is the implementation of a suitable synchronization algorithm, needed to ensure proper operations and the injection of the maximum amount of energy while avoiding instabilities and/or failures. It is usually based on phase-locked loop (PLL) or its variants: synchronous reference frame (SRF-PLL), enhanced phase-locked loop (EPLL), quadrature phase-locked loop (QPLL) and dual second-order generalized integrator (SOGI) [25–26].

When dealing with PV generators in DG, there are many issues that depend on both the power level and the input and output voltage. The choice of plant as well as converter topology is important for extracting the highest amount of power by PV cells, ensuring the optimum connection between the converter and the grid and implementing protective functions. It is necessary to balance electrical considerations such as voltage and current levels, power losses, robustness, reliability, expandability, complexity, cost and actual operating conditions (e.g., sunlight level and its daily/monthly distribution, shadowing effects and so on), which play a role often more important than technical and/or technological issues. Often large PV plants are microgrids (MGs), that is, small autonomous systems interconnected with others and/or with higher hierarchical level power grids. In low-power applications (few kilovolt-amperes), typical systems include a simple high-frequency DC/DC converter (boost or buck-boost) with or without a high-frequency transformer and a single-phase PWM inverter.

New converter topologies such as resonant DC/DC converters are being considered, with the aim of increasing efficiency and reducing costs and size. Cells are arranged such that the highest efficiency is achieved: due to the relatively high number of cells, the PV field surface is quite limited (some tens of square meters) and hence shadowing effects caused by clouds or other random obstacles interposed between the sun and the panels are almost negligible if certain precautions are taken during the positioning of panels. On the other hand, in order to avoid performance drops, cascaded cells require higher consistency of their electric characteristics compared to a parallel arrangement. Hence, the choice of series or parallel connection is not unique and always represents a trade-off.

Recently, "plug-and-play" solutions have been proposed: each single panel has its own complete power converter, and thus it can be directly interconnected with the grid [27].

This solution has some advantages: high modularity, quick installation, high reliability, optimized performance and reduced losses because of the direct availability of AC output voltage and simple maintenance (in the case of failure of a panel, the others and hence the whole system, continue operation and the faulty panel can be easily replaced without service interruption). Alternatively, each panel can incorporate its own DC/DC converter, thus allowing its accurate control and optimization, while the DC/AC conversion is provided by a system-level inverter [28].

This approach seems to be very attractive as the cost of the low-power DC/DC converter is not high, while accurate MPPT and fixed DC voltage are ensured at panel level.

Medium- and high-power systems require some choices imposed by a number of distinct factors including the following:

- PV field electrical arrangement (i.e., series or parallel connection of panels) due to electrical and shadowing factors

- the limited power achievable by insulated DC/DC converters due to the unavailability of large ferrite cores
- the choice of output current/voltage
- the choice of the inverter (single inverter or multiple inverters in parallel)
- the intrinsic problems of MPPT in large systems
- the presence of low-frequency transformers between the PV plant and the grid.

Also in this field, plant technology is moving toward modular solutions, which basically consist of a double-stage power converter (high-frequency DC/DC converter and inverter) for each string of the PV plant, the latter producing a relatively high amount of power.

Single-phase inverters may be considered for each string, achieving three phases at the grid level. In this case, blocking diodes are not requested, MPPT algorithms are applied separately to each string and accurate power control can be achieved.

Alternatively, several DC/DC converters may be connected to a high-voltage DC bus, the latter linked with a single or multiple three-phase inverters. The DC/DC units can be current source converters or voltage source converters.

The first type is preferred due to its high robustness; the other requires large electrolytic capacitors, which are bulky and have low reliability due to their intrinsic degradation because of aging. Alternatively, numerous expensive polypropylene capacitors might be used, guaranteeing constant performance without any degradation or influence by ambient temperature. Whatever the choice, modular designs improve reliability and performance, but at the cost of higher complexity.

New topologies have been recently proposed in order to increase efficiency or reduce cost or both. Among them, a very interesting solution is the use of cascaded H-bridge multilevel converters, consisting of a number of H-bridges connected in series, each one supplied by a separate PV generator connecting a suitable group of cells in series and/or in parallel, thus reaching the desired level of input voltage without the use of additional converters. This architecture, also known as cascaded multilevel inverters (CML), allows better utilization of the available input energy because each H-bridge can embed its own MPPT algorithm; moreover, suitable voltage levels can be chosen, thus extracting the highest amount of solar energy without the need for a DC/DC converter, while conversion efficiency is higher due to the lower switching losses resulting from lower switching frequencies.

Faster and more efficient power devices can also be employed due to the lower operating voltage of each H-bridge, further improving overall performance. In high-power high-voltage (kV) applications, direct operations are allowed without the need for line frequency transformers or high-voltage DC sources. Another significant advantage of CML inverters is their better output waveforms, which achieve a significant reduction of the output filter and an increase in the efficiency of PV energy conversion.

3.4 Wind and Mini-hydro Generators

Wind and mini-hydro systems use AC synchronous or asynchronous generators that convert the mechanical energy generated by wind or water and available at the machine shaft into electrical energy.

The simplest high-power wind generator consists of a squirrel-cage induction generator (SCIG) connected with the grid through a transformer. Owing to its simplicity and the intrinsic induction machine behavior, it can operate at an almost fixed speed and in the presence of a stiff grid. Its limited control capabilities are often achieved at a mechanical level (e.g., blade pitch control), while reactive power control requires the availability of a STATCOM.

Current power electronic technologies and devices offer more sophisticated solutions, such as multipole permanent magnet or induction generators connected with an AC/AC or an AC/DC/AC power converter capable of stabilization of both voltage amplitude and frequency at the desired levels. Generator sets operate at voltage levels starting from 400 V, 50 or 60 Hz, up to some kilovolts, the latter being typical of multi-megawatt systems. However, typical generators operate at voltage levels lower than the grid and therefore their interconnection requires the use of a line-frequency step-up transformer. It is worth noticing that the use of multilevel converters might allow the elimination of such a transformer.

Depending on the power level and the required performance, the power converter consists of a simple unidirectional diode rectifier coupled with a PWM inverter (or any other topology) through a DC link or the more sophisticated back-to-back converter, providing bidirectional power flow. The inverter is coupled with the grid through a low-pass filter, needed to ensure the elimination of high-frequency harmonics and a line frequency transformer.

In the range of very high-power generators (hundreds of kilovolt-amperes up to several megavolt-amperes), doubly fed induction generators (DFIGs) represent a very common and interesting solution because of their high efficiency, full control of active and reactive power and the need for a converter with a rating of about 20–30% of the generator power. In fact, the machine stator windings are directly connected with the grid or with each interposed line frequency transformer, while full active/reactive control is achieved by modifying the supply characteristics of wound rotor windings through a power converter. This reduces power converter cost, saves energy (reducing power converter losses) and extends the power range (limited by the power devices rating). DFIGs may operate in the kilovolt range and the power converter could consist of a matrix or a multilevel converter [29–31].

In low-power applications, a DC/DC converter might be included in a DC link for MPPT, but the available technology of magnetic materials limits their use to a few tens of kilowatts (Figure 3.3).

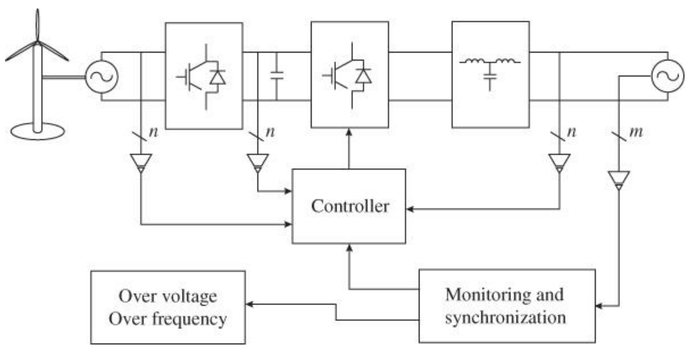

Figure 3.3 Schematic diagram of a wind generation system

3.5 Energy Storage Systems

The intermittent or fluctuating operations of RESs can be mitigated by energy storage systems (ESS) [32].

Traditional systems consist of hydro and pumped storages. Their capabilities are often enormous, but usually they are very far from loads and/or wind or sunlight generators. Consequently, their effects in the event of voltage sags, swell, or other transient disturbances are negligible, while they are important in balancing long-term predictable fluctuations, which can be eliminated through suitable accumulate–release energy strategies. Recently, mini-hydro and micro-hydro have been gaining diffusion. Their localization is intrinsically less critical, but their operations cannot satisfy fast peak demands, except when they are controlled by demand prediction [33].

Typical energy storage systems for fast transient operations are batteries, supercapacitors, freewheels and fuel cells.

Batteries appear to be the most effective technology available today in terms of performance and costs, even if their reliability and duration are not outstanding. Traditional lead acid batteries are leaving space to other technologies such as nickel–metal hydride (Ni-HM) and lithium-ion batteries (in some variants), which present higher capacity and faster recharge time. Batteries allow a fast transient response, satisfying the most demanding applications, but their drawback is a long recharge time.

Supercapacitors have an energy density hundreds of times greater than that of conventional electrolytic capacitors and a power density much higher than that of batteries or fuel cells; their speed in supplying current is very high but their voltage level is too low for requirements so a lot of cells must be connected in series in order to reach the desired voltage level; hence, their cost is not yet attractive.

ESSs are needed for quick delivery of energy, and thus heat-based sources are needed for long-term disturbances caused by predictable meteorological variations.

ESSs can be either DC or AC sources. In the first case, they are usually connected with a DC link shared with the existing power converters. The cost of this solution is attractive but the achievable power is often limited; moreover, it has low flexibility and low stiffness to failures, sharing the DC/AC converter with RES. A better solution consists of a fully independent ESS directly connected with the AC grid, as each element can be sized independently and easily modularized.

Local or residential micro storage systems (MSSs) will be integrated with the end-users of future SGs, allowing utilities to dispatch stored energy produced earlier by local generators. To perform data gathering and control, the ESS should communicate with other devices, such as the power meter, to monitor the power consumed.

3.6 Electric Vehicles

Electric vehicles (EVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) use electricity either as their primary fuel or to improve the efficiency of conventional combustion engines [34]. All of them use a lithium battery (or other recent technology) to store the electrical energy needed to power the motor. Their diffusion is expected to grow very quickly during the next few years, as their cost, considering a balancing between various costs (purchase, use, maintenance, disposal), will become similar to or better than that of traditional combustion engine cars. For this reason, they are being considered as a viable solution for energy storage in SGs through the so-called vehicle-to-grid (V2G) technology: during recharge operations, the vehicle battery and recharge system are in parallel with the grid; therefore, using a bidirectional converter for recharge and following a suitable demand side management strategy, the vehicle can supply energy to the grid like any other storage system [35]. The main drawback of this strategy is represented by the limited quantity of available electricity, which is strictly dependent on the capacity of the installed batteries. In fact unlike "static" ESS, battery recharge is very common in V2G because of the main use of the vehicle. On the other hand, using proper recharge operations at high power, a typical car could be recharged within 20–30 min. With present technology, this is only possible when operating connected with a 400 V three-phase line sustaining currents of around 150–200 A. These kinds of recharge operations require accurate control of both electrical quantities and main battery parameters; otherwise, the battery life may be very short or the battery might be seriously damaged [36–37]. Moreover, the huge quantity of electricity necessary to recharge EV fleets is evident. This last aspect is crucial and requires large investments in the power system infrastructure. Alternatively, relatively small electric generators (some megavolt-amperes), for instance CHP, might be installed in the vicinity of parking with the dual task of recharging batteries and providing heat to nearby buildings. An interesting solution is represented by use of PV energy: large PV plants can be realized by exploiting the surfaces of roofs of shopping centers or by creating covered parking.

3.7 Microgrids

With the advent of DG and SG, power systems are moving toward a different scheme with a huge number of reduced scale systems, called microgrids (MGs), interconnected by meshes of complex transmission lines, whose nodes have a high level of intelligence. MGs could be interconnected among them at a distribution line level [38–39].

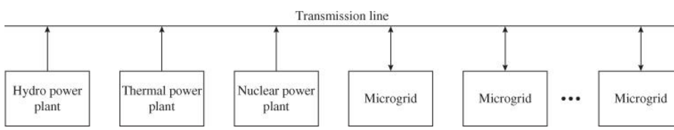

Figure 3.4 Power system with microgrids

Each MG is autonomous and includes electricity generators, energy storage, distribution lines, loads and interfaces with the higher level grid called common coupling point (CCPs), where the higher level grid is often referred to as the macrogrid. MG operates at low- and medium-voltage levels. This operation mode is known as "islanding." CCPs include line frequency transformers and protection and intelligent devices with communication capability (Figure 3.4).

This approach has several advantages. In fact, owing to the high modularity and local use of energy, it simplifies the system; eliminates transmission losses; improves efficiency; provides active load control; isolates MGs from foreign disturbances, failures and outages; and simplifies self-healing, thus increasing the resilience of the overall system [40–41].

The quantity of energy generated in an MG usually corresponds to local demand, but the concept is general and therefore it could be applied to wind farms or other similar systems, where most elements are generators. Connections with higher hierarchical levels occur only to satisfy peak demands that cannot be handled locally, to buy energy produced in other MGs, or to sell energy. Generators are supplied by RESs, but in order to limit the drawbacks of RESs (energy fluctuations and daily variations), they are integrated with fuel-based generators, typically TG eventually supplied by biomass, or CHP systems (Figure 3.5).

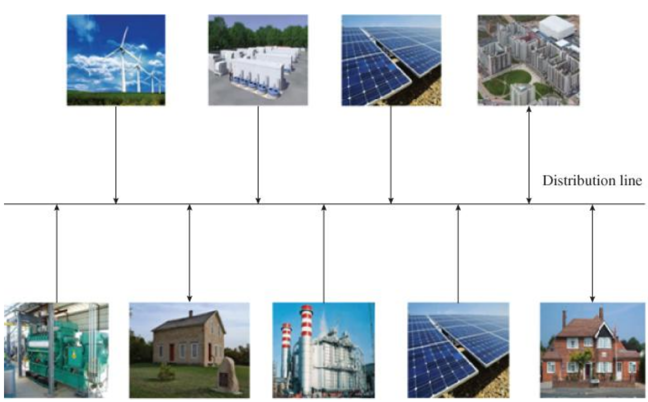

Figure 3.5 Example of microgrid

In the future fuel cells could replace integrated thermal power plants but nowadays their cost is prohibitive.

The use of no-RES generators depends on the level of intelligence of the system, its predictive capability and the location of the MG. Typical TG generators reach their full power within a few seconds, and hence they might be operated on a prediction basis, thus supplying electricity only when RESs are not sufficient to cover peak demand or during the night and more generally during periods with limited sunlight or wind due to adverse weather conditions. This could allow the use of "foreign" energy to be avoided or limited to exceptional circumstances [42].

In order to ensure stable operations and the necessary power quality, energy storage systems must be included in an MG. Their quantity and dimensions depend on several factors, including the number and type of loads, the quality of energy available in the MG and the possibility of operations tightly connected with the grid.

3.8 Smart Grid Issues

Connecting RESs with the grid and managing a MG or a SG may become a challenging task if the number of generators and users is very large and their power quality and/or that of the grid is not high. Therefore, optimal operations can be achieved only by addressing stability and reliability issues. Moreover, the intrinsic nature of DG imposes flexibility and expandability.

Dynamic perturbations caused by interactions among fluctuating power sources and variable loads often lead to instabilities, which, if not adequately controlled, might cause failures and blackouts. These situations can be reduced by introducing large storage systems and in a well-designed MG, they are intrinsically less frequent and easier to manage. Instability should be taken into account while designing power system and power converters in order to either eliminate it at source or mitigate its effects.

Suitable protection policies and control algorithms can be implemented using both HW and SW, eliminating the risk of network instabilities and failures of power sources or power converters. This approach requires real-time sensing of output quantities (voltage, current, frequency) and, eventually, fast breakers capable of real-time disconnection of elements from the grid, thus preserving its integrity. Well-designed inverters can intrinsically avoid the injection of additional energy in an already unstable system and, in some circumstances, operate similar to that of a STATCOM or a Unified Power Factor Controller (UPFC). For instance, they can provide active and reactive power. Such systems usually adopt PLL techniques (already listed in an earlier section) and zero-crossing grid voltages detection (ZCD) implemented through a group of combined filters coupled with a nonlinear transformation. The latter approach may be negatively influenced by poor power quality determined by electromagnetic interferences (EMIs) and other disturbances, such as random voltage sags, swell and dips, which may lead to erroneous triggering and time delays. These drawbacks can be mitigated using appropriate design techniques and filters.

STATCOMs and UPFC, eventually coupled with supercapacitors, are typical power converters specific for dynamic stabilization.

Instabilities caused by long-term fluctuations or other disturbances as well as by the effects of remote failures can only be managed through the availability of energy storage systems (e.g., batteries) and converters with appropriate capability, and, if this is not successful, through the use of hydropump plants or, at worst, disconnection.

Wide-area situational awareness (WASA) systems integrate technologies for effective power system management and monitoring. They represent one of the key functions of SGs, since they provide reliability, security and interoperability among so many interconnected systems and devices. Synchrophasors are counted as new wide-area measurement technologies. Their primary task is to measure the different portions of the power system and to put these measurements on the same time basis, enabling a view of the whole power system at the same time and thus simplifying the comparison of different portions of the power system in real time.

Reliability is another important requirement in DG and SGs. Similar to other fields, it can be achieved by adopting best practices during design and realization of single elements and of the whole power system. The availability of a network of sensors and actuators, typical of SG, is commonly exploited for implementation of early prediction, fault detection and diagnosis. Power converters and the other intelligent systems connected with an SG usually include sensors and feedback control, and therefore they embed self-protection mechanisms and, eventually, self-healing.

In conclusion, DG and SGs intrinsically address the problems of energy flow optimization, flexibility and expandability. However, these performances can be greatly improved by using new HW systems as well as sophisticated and high-performance SW techniques capable of addressing the high complexity of the problem. For instance, the approach based on smart agents, recently proposed for control and management of SGs, reduces problem complexity by splitting the complex system into many simpler elements (agents) and defining a set of behavioral rules. Other ongoing researches use different approaches to reach the expected results.

3.9 Active Management of Distribution Networks

Active networks (ANs) consist of local areas with full integration, at control level, of distributed generators, network devices and customers, with the aim of balancing the electrical energy supply and demand, thus obtaining a better utilization of the available energy and more reliable operation. This enhances overall performance, offering new system services such as flexible voltage regulation, optimized power flow paths, congestion management, fault isolation, situational awareness, outage management, distribution automation, distribution management, asset management, smart metering, demand response management, management of other individual customers, and full network security [43–45].

ANs could be defined at an MG level, or in the case of high complexity, an MG could include a distinct AN area.

By virtue of the extensive use of ICT and an advanced metering infrastructure, the distribution network fully connects (power + data paths) suppliers, distributed system operators (DSOs) and customers; hence, ANs permit full coordination among generators, voltage regulators, reactive power compensators, on-load tap changers, loads and all other network devices. The information exchanges are used both for network management, thus to ensure optimum operations and a high level of security and for sophisticated billing management, thus for full exploitation of energy market operations [46–50].

This approach allows significant advantages in terms of efficiency of the power system and better utilization of physical infrastructure, in particular the distribution lines, resulting in a reduction or deferral of network investments. Some researches have demonstrated the economic benefits deriving from active management as compared with traditional network reinforcement strategies.

Ongoing research projects on the management concepts of ANs are focused on the resolution of interconnection issues of DGs. At the entry-level stage, AN management consists of monitoring and remote control of DG. At the intermediate stage, it permits the optimum allocation of a significant amount of DG, once the local and global services and trading issues have been defined. Full exploitation of ANs relies on overall network management.

However, due to the huge investments, new market rules are still required in order to balance the economic contribution among players in order to achieve government targets for the utilization of renewable sources and to offer economic benefits to DNOs. Therefore, in most countries, the present situation can be considered far from full exploitation of the current technical possibilities.

3.10 Communication Systems in Smart Grids

The communication infrastructure connecting energy generation, transmission, distribution systems and consumption points is an essential component for the development of an SG and to ensure full operations, security, reliability, flexibility, response demand management and other important features. The adopted technologies are fully digital, thus enabling data digitization, intelligent self-awareness and increased reliability.

SG communication infrastructures can be public or private. Public networks like the Internet and the 2G, 3G and 4G mobile networks are excellent and are at low cost, but due to the existing communications, their use may lead to several problems. Among them the most evident are the difficulty of achieving effective real-time and reliable communication and security issues. These issues can be addressed by defining suitable virtual private networks (VPNs). Power distribution lines themselves act as communication carriers by using Power Line Communication (PLC) technology, coupled with a combination of wired and wireless technologies, thus creating a complex but reliable communication infrastructure [51].

Due to the complexity and critical nature of problems, standardization of HW and SW communication technologies specific for SG applications is fundamental for successful operations.

The selection of a suitable communication architecture is subject to many challenging technical restrictions regarding the needs of bidirectional and real-time communications, interoperability between applications and reliable communications with low latencies and sufficient bandwidth [25]. Bandwidth, speed and real-time requirements depend on the specific application; for instance, billing information requires a very low bandwidth, while fast information exchanges are fundamental for early prevention of or system recovery from outages. Moreover, high system security has to be ensured to prevent cyber attacks and to provide power system stability and reliability.

A first element in the design of an SG communication infrastructure is the consideration of the system's scalability, as this greatly simplifies the system design, operations and maintenance.

Another fundamental element is usability, which can be easily achieved by using common interfaces such as a Web server, which is easily reachable and configurable using traditional and widely known browsers at SW level and widely diffused interfaces and protocols (e.g., Ethernet, Wi-Fi, ZigBee) for interconnection of nodes. However, due to security issues, they require some enhancements over general purpose applications.

Interoperability, that is, the ability of SG components to work cooperatively, exchanging information is another requirement. This requires adoption of some standards across the communication network.

There are two IEC standards (61970–301 and 61968–11) that are capable of describing different components and their interrelationships within a hierarchical architecture. Moreover, the IEC 61850 standard aims to improve the interoperability between Intelligent Electronic Devices (IEDs) for substation automation systems, while the IEEE P2030 standard provides interoperability between the electric power system (EPS) and customer-side applications, and the ANSI C12.22 standard is for communication modules and smart meters [19].

Quality of service (QoS) is another important requirement. Performance degradation such as delays or outages may compromise stability; therefore, QoS mechanisms must be provided to satisfy communication requirements. Usually they include specifications such as average delay, jitter and connection outage probability. To derive the QoS requirement, it is important to describe the probabilistic dynamics of the power system needed to evaluate the impact of different QoS specifications on the SG system and to derive the QoS requirement from the corresponding SG system.

In both wired and wireless networks, a very important problem is the availability of robust routing infrastructures, which are fundamental for reducing the influence of the above problems. Hybrid routing protocols that combine local agility with centralized control are still under development.

Other problems are the remote location of nodes, requiring very low-power electronic devices and lossy environments, where the presence of high interference requires adaptive and reconfigurable network operations.

Communications can be divided into three distinct categories or layers [19]:

- Wide area networks (WANs)
- Field area networks (FANs)
- Home area networks (HANs).

The three main tiers that are located between these three networks are the core backbone, back-haul distribution and access point.

The communication between back-haul aggregation points and the core backbone utility center is carried over different types of communication networks, such as star networks and fiber or wireless networks. In the following, a brief description of transmission categories is given:

- WANs provide high-bandwidth communications between electric utilities and substations for sensing, monitoring and control of the SG. Cellular networks, WiMAX and wired communications can be used for WAN, but fiber and microwave communications are preferred for their higher bandwidth and reliable communications. PLC is also possible but with reduced bandwidth [54]. Wired communications are better from a security point of view because of their intrinsically low possibility of cyber attacks.
- FANs act as bridges between customer premises and substations. Wireless communications such as Wi-Fi, WiMAX and Radio Frequency (RF) mesh technologies are suitable for FAN communications. Smart meters, advanced distribution automation and integration of distributed

energy resources are some of the areas of application of FANs.

- HANs are connected with FANs by smart meters. HANs are low bandwidth and support communications among home electrical appliances and the smart meter. Many functions are implemented on HANs: smart metering, customers' information about their own consumption and electricity market opportunities (e.g., prediction of energy cost during the day) for optimum load management and communication with the FAN if the customer produces energy, for instance, with PV panels. Many interesting functions will be available in the future at HAN level for implementing intelligent load management. ZigBee, Wi-Fi, HomePlug, Z-wave and M-Bus are suitable for the HAN category. ZigBee has the ability to operate in a mesh network topology, which offers some advantages; that is, some devices in a ZigBee mesh can remain in sleep mode when they are not active in the network, which results in energy conversion. Wi-Fi cannot support mesh networking and is more expensive and more energy hungry. On the other hand, Z-wave is an interference-free wireless standard that is specifically designed for the remote control of appliances and widespread for HANs.

3.11 Advanced Metering Infrastructure and Real-Time Pricing

Smart metering and advanced metering infrastructures (AMIs) are fundamental in SGs. They create a bidirectional communication channel between provider and user, thus allowing cooperation among remote advanced sensors, monitoring systems and all computers, SW and data management systems available in a modern smart home connected with the SG, thus allowing consumers' participation in the energy market. The AMI includes a meter data management system (MDMS), located at FAN level, necessary for handling the huge amount of data and managing the raw data, creating meaningful information and messages for customers and assisting them in using energy intelligently. The same infrastructure can be used for managing information generated by different technological networks, such as electricity, gas, water and – if in the vicinity of a CHP thermal plant – heating. The most known advantage of AMI is that customers can participate in the energy market by changing their energy consumption instead of being passively exposed to fixed prices, resulting in profits for both service providers and end-users, but it also ensures the best SG performance (Figure 3.6) [55].

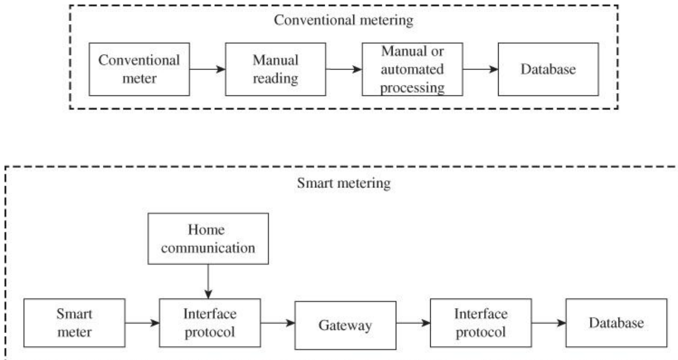

Figure 3.6 Smart metering

AMI can use different communication technologies, whose choice depends on the number of customers and the coverage per area, the availability of Internet connection, the scalability, the required data rate and expected communication delay, the expected energy efficiency and so on.

Low latency and high bandwidth are essential for some AMI critical applications, such as recovery from remote failures or elimination of incipient failures detected early, thanks to the available sensors network. PLC is widely diffused in urban areas, but may be insufficient for some real-time applications requiring bandwidths up to 100 kbps per device. The availability of optical fibers could solve the problem while increasing the number of services, too. Instead, RF meshes, GPRS and other cellular transmissions are the only viable technology to connect low-density areas. Therefore, in rural areas, smart meters are connected with MDMS by using wireless communications.

In order to successfully implement home energy management (HEM), consumption data gathered from each appliance are measured and transferred to a data concentrator, which could be the smart meter itself. Hence, data can be used locally to inform customers about their consumption behavior or for their active control and are also sent to the utility company for accounting and to enable remote response demand management. As already pointed out, ZigBee is currently considered an excellent solution for HEM networks. HomePlug and Bluetooth technologies could also be considered, but their cost is not dissimilar to that of ZigBee, while their performances are often lower (Figure 3.7).

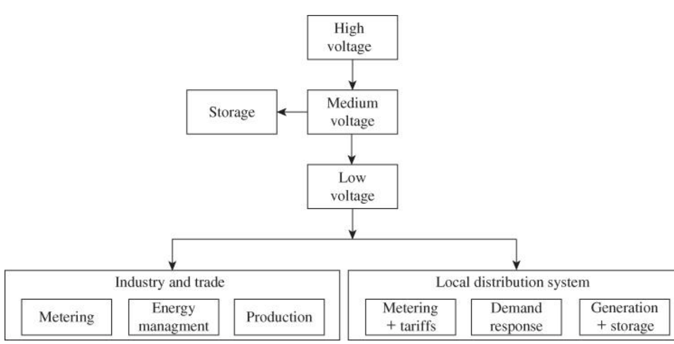

Figure 3.7 Advanced metering infrastructure

3.12 Standards for Smart Grids

Full standardization of DG and SG devices and protocols is necessary to guarantee proper operations with high efficiency, reliability and security. Indeed, efficient and reliable operations can be achieved only by adhering to standards.

Because of the complexity and the wide spectrum, numerous distinct standards have been proposed and often revised to fit with the new developments for SG while others are under study.

Important standards with regard to the characteristics of DG and SGs are IEEE 1547, IEC 61850-7-420, IEC 61400–25, IEEE 1379, IEEE 1344 – IEEE C37.118 and IEEE 519.

IEEE 1547 is the standard for interconnection of distributed energy resources (DERs) and was published in 2003. It gives a set of criteria and requirements for the interconnection of DG resources into the power grid. Currently, there are six complementary standards designed to expand upon or clarify the initial standard, two of which are published, while the other four are still drafts.

IEC 61850-7-420 represents the standard related to communication and control interfaces for all DER devices. This standard defines the information models to be used in data exchange among DERs, which comprise

DG devices and storage devices, including fuel cells, microturbines, PVs and combined heat and power. Where possible, it utilizes existing IEC 61850-7-4 logical nodes and defines DER-specific logical nodes where needed. Such standards allow significant simplifications in implementation, reduction of installation costs, sophisticated market-driven operations and simplification of maintenance, thus improving the overall reliability and efficiency of power system operations.

IEC 61400–25 defines the communication needed for monitoring and control of wind power plants. It is a subset of IEC 61400, a set of standards for the design of wind turbines. The standard allows control and monitoring of information from different wind turbine vendors in a homogeneous manner. The information is hierarchically structured and covers, for example, common information regarding the rotor, generator, converter, grid connection and the like. It covers all components required for the operation of wind power plants including the meteorological subsystem, the electrical subsystem and the wind power plant management system.

IEEE 1379 is the recommended practice for data communications between remote terminal units and intelligent electronic devices in a substation. This standard, published in 2000, provides a set of guidelines for communications and interoperations of remote terminal units (RTUs) and intelligent electronic devices (IEDs) in a substation. It does cover two widely used protocols for Supervisory Control and Data Acquisition (SCADA) systems: IEC 60870–5 and DNP3.

IEC standard 60870–5 deals with telecontrol, teleprotection and the associated telecommunications for electric power systems. It provides a communication profile for sending telecontrol messages between two power substations and defines operating conditions, electrical interfaces, performance requirements and data transmission protocols.

DNP3 (Distributed Network Protocol) is a set of communication protocols used between components in process automation systems. Recently, IEEE adopted DNP3 as IEEE standard 1815–2010 in 2010 and then modified it in the present standard 1815–2012.

Standard IEEE C37.118 is the current standard for measurement systems of synchronized phasors [56]. Synchronization is fundamental for ensuring proper operations and for eliminating potential faults and failures. A phasor measurement unit (PMU), which can be a stand-alone physical unit or a functional unit within another physical unit that estimates an equivalent synchrophasor for an AC waveform, is introduced. The total vector error compares both the magnitude and the phase of the PMU estimate with the theoretical phasor equivalent signal for the same instant of time. It provides an accurate method for evaluating the PMU measurement and establishes compliance requirements under steady-state conditions. The latter define the levels for phasor frequency, magnitude and angle measurements, harmonic distortion and out-of-band interference. It is worth noticing that IEEE C37.118 does not establish compliance requirements under dynamic conditions or other tests during which the amplitude or frequency of the signals varies, even if several dynamic tests are described in this standard.

IEEE 519 establishes the limits on harmonics amplitudes for currents and voltages at the PCC or at the point of metering in an EPS. The limits assure that the electric utility can deliver relatively clean power to all customers and protect its electrical equipment from overheating, avoid loss of life from excessive currents harmonics and prevent excessive voltage stress because of excessive voltage harmonics.

IEEE P2030 deals with interoperability of energy technology and information technology operation with the EPS and customer-side applications. It is responsible for bidirectional data transfer for electricity generation and reliable power delivery.

IEC 62351 is a standard for cyber security and protection of communication protocols from hackers' attacks.

Other standards have been defined for communications in WANs, FANs and HANs, for example, G3-PLC, HomePlug, PRIME, U-SNAP, IEEE P1901, Z-Wave, IEC 61970 and IEC 61969 and IEC 60870–6.

Finally, V2G operations are regulated by SAE J2293, which provides the requirements for EVs and electric vehicle supply equipment and SAE J2836 with regard to the communication between plug-in electric vehicles (PEV) and power grid, while SAE J2847 is specific for communications between PEVs and grid components.

In conclusion, numerous international standards regulate almost all aspects of DG systems and SGs, thus obliging equipment producers and users (service providers, generator builders and final users) to fulfill standard requirements to guarantee smooth and correct operation of the whole SG.

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