Introduction—Advances and Challenges in Active Distribution Systems

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Abstract Many drivers are determining continuous changes in the structure and operation of distribution grids. In addition to the now long-lasting effects introduced by the smart grid paradigm, a number of new trends are emerging. This chapter provides an overview of how distribution systems are changing. Modernisation is the key point to pass from network infrastructures designed in a rather different context to new solutions that incorporate advanced features. For this purpose, the concepts of passive user, active user, and prosumer, and their role in emerging distribution systems, are introduced and discussed. Relevant aspects addressed include the impact of the diffusion of renewable energy sources in the operation of distribution systems and microgrids, as well as the current trends towards establishing local energy markets and energy communities. Further aspects refer to the development of local solutions for the generation, management and storage of energy at small- and micro-scale, the increasing attention towards grid-side and demand-side flexibility, and the provision of grid services.

Acronyms

ADN Active Distribution Network
ADS Active Distribution System
AS Ancillary Services
BMS Building Management System
CHB Cascaded H-Bridge
CHCP Combined Heating, Cooling and Power
CSC Current Source Converter
DER Distributed Energy Resources
DG Distributed Generation
DLMP Distribution Locational Marginal Price
DR Demand Response
DS Distributed Storage
DSO Distribution System Operator
EMI Electromagnetic Interference
ESP Energy Service Provider
ES Energy Storage
EV Electric Vehicle
FACTS Flexible Alternating Current Transmission Systems
FLC Flying Capacitors
GTO Gate Turn-Off
HV High Voltage
HVDC High Voltage Direct Current
ICT Information and Communication Technologies
IEGT Injection Enhanced Gate Transistor
IGBT Insulated Gate Bipolar Transistor
IGCT Integrated Gate Commutated Thyristor

LCC Line Commutated Converter
LV Low Voltage
MG Microgrid
MGMS Microgrid Management System
MMC Modular Multilevel Converter
MMG Multi-Microgrid
MV Medium Voltage
NG Nanogrid
NOP Normal Open Point
P2P Peer-to-peer
PCC Point of Common Coupling
PCT Phase-Controlled Thyristor
PDS Primary Distribution Substation
PV Photovoltaic
PWM Pulse Width Modulation
RES Renewable Energy Sources
RMS Root Mean Square
SC Self-Consumption
SDS Secondary Distribution Substation
SGAM Smart Grid Architecture Model
SS Self-Sufficiency
SST Solid-state Transformer
TE Transactive Energy
THD Total Harmonic Distortion
TSO Transmission System Operator
V2X Vehicle-to-Everything
VPP Virtual Power Plant
VSC Voltage Source Converter
WBG Wide BandGap
WoC Web-of-Cells
WT Wind Turbine

1.1. The Main Drivers for Distribution System Modernisation

The restructuring of the electricity business has taken place since the last years of the last millennium, and has become widespread around the world since the beginning of the current millennium. The unbundling of the electrical generation, transmission, distribution, and retail sectors has required establishing new operators inside each sector. In particular, the electricity distribution sector has been generally managed by partitioning the territory into different areas of competence. After unbundling, the role of the Distribution System Operator (DSO) was assigned to a unique entity in each area of competence. Meanwhile, historical areas in which there were more electricity distributors were re-organised by specific agreements (or legal arbitrages) to maintain only one DSO. The distinction between distribution and retail has led to the birth of a competitive framework in the retail sector, and to the establishment of DSOs as the technical operators that act on their distribution networks.

The unbundling of the electricity sectors required to deeply analysing the characteristics of the value chain inside each sector, with the aim of clearly identifying the specific costs and benefits. For the distribution systems, the situation that emerged was generally the one of an electricity distribution infrastructure designed many years before and operated in a centralised way. The need for modernising this infrastructure was clearly highlighted by the concomitant appearance of a number of factors, among which:

- Growing attention towards environmental impact issues, in particular after the Kyoto Protocol.

- The development of technologies for energy production from renewable energy sources (RES), which reached an appropriate technological maturity.
- The possibility of introducing distributed generation (DG) in the distribution systems, not only supplied by RES.
- The evolution of technical solutions for electrical storage, including the progressive introduction of electric vehicles (EVs).
- The disclosure of the possibility to supply power to the grid, leading to enabling active distribution networks (ADN) with power injections not controllable by the DSO, and connection limits determined by newly established regulators and authorities.
- A fast evolution of the information and communication technologies (ICT), which made available advanced communication systems and controls, and several tools to assist the distribution system analysis, operation and planning.
- The development of an extended economic framework based on competition among various players, also with the creation of new players with various roles.
- The changing role given to the demand side, also considering the *participation* of the users to the provision of electricity, either with the combined role of producers-consumers (or *prosumers*) or depending on the users' willingness to provide *demand response* (DR) services based on price signals or incentives.

A few years later, many of these principles were considered under the smart grid paradigm (Amin 2004), applied in the Smart Grids Technology Platform of the European Union (European Commission 2006) and in the U.S. Energy Independence and Security Act of 2007 (U.S. 2007). Under the smart grid paradigm, some aspects were further emphasised, including cyber-security, energy conversion through power electronics devices, and flexibility of the supply and demand. It is worth noting that the terms "smart" associated to "grid" was used, probably the first time, in the document (Vu et al. 1997) as an acronym for Self-Managing And Reliable Transmission Grid, to indicate a monitoring, control and protection automated system that, with the use of ICT and new algorithms, allows improving the reliability of the transmission system. Nowadays, the term smart grid mainly indicates the evolution of the *distribution* system, which needs to be modernised more than the transmission system. The term Distributed Energy Resources (DER) is also typically used to define the merging of DG, DR, and Distributed Storage (DS).

In addition to the classical attributes of reliability, stability, security, efficiency and cost effectiveness, the new systems have to be smart, sustainable, resilient and interoperable, contributing to the energy transition in progress, in which the role of electricity is going to become more and more significant for all the end uses (residential, industrial, commercial, and transportation).

Specific aspects are detailed in the next sections:

- active distribution networks
- network structures
- renewable energy sources
- energy conversion
- operational aspects
- economic aspects
- energy management aspects
- grid services

1.2. Active Distribution Networks

The past distribution system was an infrastructure than aimed to connect the upper level (high voltage) system to the *passive loads* of customers that required active and reactive power from the grid. The auto-production was limited to very large customers connected at high-voltage system, and the possible injection of active power into the grid was always agreed with the system operator. Consequently, most of the analysis carried out about the distribution systems so far considered only the *demand level of the system* (Kersting 2002): aspects such as the maximum and average demand, the load factor, the *diversity* of the demand, the design based on voltage drop and/or power losses took a relevant part in any book. The presence of *time-variant load* was not taken into account because it was sufficient to consider the worst-case scenario for design. For this reason, there was no interest to investigate the *operation* of the system at the planning and design stages.

However, the innovation in the generation side, with the introduction of new local generators that exploit RES, changed dramatically the idea of distribution system operation: for the first time after the introduction of the alternating currents, researchers and technicians started thinking that producing locally could conveniently drive the change in the paradigm of the whole electricity system operation. Hence, two different paradigms started to face each other, based on completely different visions of the electricity system: on the one hand, the future shape of the system could be based on the development of the *super-grids* (Shettler et al. 2012), whereas on the other hand the future system could be seen as composed of *micro-grids* (Lasseter et al. 2002). In the former case, the main infrastructure is the transmission system, which is developed to cover long distances and brings the electricity where it is needed, by exploiting the time shifts among different regions in the world. Vice versa, the latter paradigm points to develop local production and consumption, with the transmission system as the "back-up" infrastructure. In the middle of these two visions, there is enough space for another framework, based on Active Distribution Networks (ADNs) that form an Active Distribution System (ADS). The ADN (and consequently the ADS) is composed of a *number of sets* including different *entities*:

- *passive equipment*: it is the set that forms the *power hardware* of the electrical network. In this set one can find all the elements that allow secure and reliable electricity flows, i.e., transformers, cables, overhead lines, circuit breakers, relays (as components, not as logics), switches, fuses, current transformers, and voltage transformers.
- *non-flexible prosumers*: this set contains all the prosumers, which manage loads or generators whose behaviour cannot be easily changed.
- *flexible prosumers:* it contains all the prosumers that somehow can modify their *net load* shape and thus are seen as source of *flexibility.*
- *market players*: even though they are not part of the ADNs, they are fundamental for managing with market-based rules the ADS. As geographical extension, they can act on one or more ADNs, and their intervention helps exploiting the flexibility of the prosumer at a system level.
- *control system*: this indicates, with a general term, all the equipment that allow the interactions among the different entities, from the ICT infrastructure to the information codification and the control logics.

The *motivation* to have an ADS is to enable the connection of a larger share of DER to the electricity system, by properly managing the uncertainties characterising the primary sources (from solar and wind energy, above all). The proper handling of the uncertainty is required for making them *fully compatible* with the operation of the electricity system: being operated in AC, the real-time balance between load and generation must be guaranteed (with small deviations recovered thanks to the existing control systems). To some extent, at the distribution system level the system operation is shifting from a *load-following* operation to a *generation-following* operation (Ponocko & Milanovic 2019), where the *load* may be modified (also involving DS) to accommodate the evolution in time of uncertain generation.

The co-existence of flexible and non-flexible prosumers leads the network operating conditions to be different in different parts of the network. A given zone or *neighborhood*, composed of one or more feeders under the same primary substation, can present voltages completely different from another zone supplied by the same substation. Furthermore, the evolution in time of the zone composition, as well as the values of current and voltage existing in each zone, may change in a non-predictable way. This characteristic does not allow finding a unique "rule", unlike it was in the past for the voltage profile, which had always a decreasing trend along the feeders. This new condition requires the introduction of new control approaches (more distributed and decentralised) and new measurements (for example on the basis of the *net load*, considering the different devices that can be connected to any node such as storage, local generators and passive load). Indicators such as the losses allocated to the system nodes (Carpaneto et al. 2008) can be useful to understand whether in a given zone there is an excess of local generation, such that to reduce the system losses it would be needed to increase the local load – a solution that had never to be considered in a distribution network with passive loads only (Mazza & Chicco 2019).

All the above-listed characteristics of the ADNs can be summarised by saying that they allow to create a *multi-layer* ADS, in which technical, economic and social dimensions co-exist. This multi-layer structure is well represented by the *Smart Grid Architecture Model* (SGAM) (Smart Grid Coordination Group 2012), which is a three-dimension structure including domains, zones and layers:

- *Domains*: the domains are the *sectors* that compose the value chain for the electrical system, i.e., Bulk generation, Transmission, Distribution, DERs and Customers.
- *Zones*: the zones reflect a hierarchy that consider the aggregation and the functional separation in power system management, and are defined according to the information managed by each of them. The zones are Process, Field, Station, Operation, Enterprise, and Market. While the first zone includes all the power system equipment and energy conversion, the other zones manage information.
- *Layers*: the layers allow highlighting the different aspects where the inter-operability among systems is required. In particular, the layers cover Components, Communication, Information, Function and Business.

It is worth noting that the role of *communication* and *information* becomes fundamental for properly managing the ADS, but also to guarantee a fruitful interaction between the different players of the electricity system.

However, *which kind* of information is required? A distinction should be made between the information *for managing the network* and the information *for enabling services*. In the first case, the information concerns the network constraints, i.e., node voltages and branch currents. This kind of information was available also in the past, but the introduction of DG shaped the electrical variables in the network differently. As a matter of example, the presence of DG at the end of a rural line can create *overvoltage* problems, which before were not even considered as potential issues (Jenkins et al. 2003). Thus, the technical measurements are able to report the existence of the problem, but the classical control actions put in place by the DSO and based on the field measurement may not be sufficient. Thus, new kinds of information are required, to engage the *prosumers* (i.e., the players that may create network issues) into the *system operation* (European Commission 2015; European Commission 2016).

This paradigm shift requires conceptually different actions:

- the definition of the *types* the information to be collected and with which *temporal resolution*;
- the collection of the information by the prosumers through the installation of *smart meters*;
- the definition about *who* is using this information and for doing *what*;
- the clear definition of the roles of DSO, prosumers and other players (such as aggregators) that are involved into the ADS operation.

The definition of the information to be collected is linked to the *services* offered by the prosumers. The types of services are strictly dependent on the market architecture and the prosumer's equipment. As a matter of example, from a technical point of view, refrigerators showed to possess all the characteristics for offering both power and energy services to the grid, spanning from frequency regulation to load shaping (Tindemans et al. 2015; Diaz Londono et al. 2020). Thus, the *value* of the services offered is not negligible. However, due the unclear definition of the roles in a new market framework (which implies, among others, interactions between the Transmission System Operator (TSO) and the DSO, the presence or not of local markets, and the method of ancillary service provision), the potential *revenues* from those services cannot be easily evaluated, unless making a number of assumptions. As recently defined in Thomson & Perez (2020) for the Vehicle-to-Everything (V2X) application, new applications and/or technologies cannot be evaluated in terms of revenues, but certainly on the *value stream*, in particular seen as *stacked stream* (i.e., possibility to provide more than one service with the same technology). The same concepts are valid for the services that, in general, the players forming the ADNs can provide to each other or to third parties (in particular to the transmission system).

Furthermore, it is worth noting that, while all the services are based on the *flexibility* of the prosumers, how this flexibility may be exploited is strictly correlated with the *willingness* of the prosumers to deviate from their baseline. According to the equipment installed at the prosumer's premises (that usually includes both generation and load, and sometimes also storage systems), the evaluation should be made on the *net load*, because the prosumer interacts with the grid with a bi-directional energy exchange. However, considering the net load can lead to some issues in the evaluation of the service value due to the scarce representation of positive and negative peaks that can be reached with the usual interval-metering paradigm that adopts time resolution of approximately tens of minutes (Chicco & Mazza 2020). Hence, at the measurement level, the proper exploitation of the prosumer's flexibility may require a large number of data, by creating problems related to data management and data transmission. New paradigms of measurement are required for the next generation of smart meters. One of the possible solutions (already commercially available) is based on the *event-driven* energy metering (Simonov 2014; Simonov et al. 2017). This solution enables tracking the demand peaks in an effective way, opening new prospects for setting up new options for tariffs or contracts for flexibility (Chicco & Mazza 2019).

Once the information is collected, *who* is in charge to use it? The current role of the DSO is basically to guarantee the proper planning, operation, and maintenance of the network, as well as the quality and security of the supply. This means that it cannot act as a *market player*, as it has to guarantee the *neutrality* the network. However, the information related to the potential flexibility of the prosumers is anyway collected through the smart meters linked to the DSO ICT infrastructure. Hence, this information should be made available to market players (such as aggregators or suppliers), which can properly manage the explicit flexibility (Smart Energy Demand Coalition 2016) of a group of prosumers collected together. The explicit flexibility is committed by participating in incentive-based programs that rely upon direct load control. These programs may be managed by the supplier or by another entity (e.g., an aggregator). Conversely, the implicit flexibility is delivered according to the sensitivity of the customer to the price signal.

Thus, the role of the DSO requires an evolution: beyond guaranteeing the *neutrality* of the electrical infrastructure, it will be responsible of the neutrality of the *measurement* infrastructure, taking care of the *security of the data* as well. Managing the information implies also the use of a proper *information model*, which defines the codification of the information: this aspect implies a great engagement of the *standardisation bodies*, which have to act for guaranteeing the maximum *interoperability* of the systems. The way in which the information is physically exchanged among the different devices is based on the *communication protocols* that can be evolved during the time (but this does not affect the information model preliminarily defined). An example of architecture which is becoming more and more common is the IEC61850, whose areas of use are becoming wider and wider.

As the last remark, the introduction of these new aspects poses key challenges also to the research field (CIGRÉ 2014). For example, the usual benchmark networks did not consider any time-variant load behaviour, and do not include any local generation. So, new methodologies have been suggested to create case studies (see for example Mazza & Chicco 2018). Furthermore, the operational constraints of the different devices have to be taken into account into the optimisation procedures, by creating more and more complex solution spaces that require new conceptual frameworks (Bahramara et al. 2020).

1.3. Distribution Network Structures

1.3.1. From Traditional Distribution Network Structures to Smart Grids

A power system consists of a set of interconnected parts to generate, transmit, and distribute electricity to the end users. These parts are interfaced by a set of transformers, which adapt the voltage to the appropriate level, suitable for the functioning of the system.

From its beginnings in the early 20th century, the structure and the organisation of the power grid underwent a very slow evolution. The generation was only based on fossil fuel and located in a central location away from the load centres; the transmission featured a mesh network structure, and the distribution was organised as a radial network to provide electrical energy at the low voltage level to the end users. Figure 1 summarises this well-known conventional structure, showing the major components of the power system: production, transmission, distribution, and consumers, interconnected through the power lines and substations.

In this conventional power system, the electrical power is generated by centralised large-scale power generation plants and it is injected, through a step-up transformer, into the transmission network at High Voltage (HV) level (230 kV, 400 kV). The transmission network delivers electrical power to the regional distribution networks, through the Grid Supply Points (GSP), which transform (step down) the voltage to the distribution HV level (100-230 kV). The distribution network delivers the received power to the end-user consumers of the networks at lower voltage levels. The voltage is first stepped down to Medium Voltage (MV) level (1-100 kV) (IEEE 2000) at Primary Distribution Substations (PDS). Then, Secondary Distribution Substations (SDS), steps down the voltage into the Low Voltage (LV) levels (<1kV), required to supply the three-phase and single-phase end-users (400 V three-phase and 230 V single-phase). Large industrial users could be connected at High Voltage (Simmonds 2002).

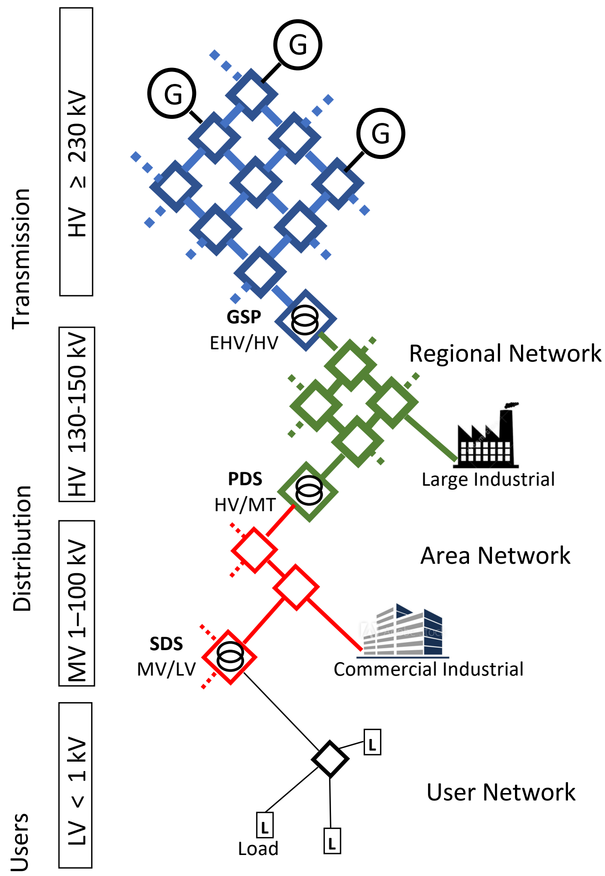

Figure 1. Conventional power system structure.

The MV distribution networks start after the PDS and terminate at a secondary distribution substation. The LV networks start from the secondary distribution substation, where the voltage level becomes 400 V in the three-phase networks. Finally, through the LV networks (230 V line to neutral), the electricity reaches the single-phase end-users (Lakervi & Holmes 2007).

The distribution networks can supply the different areas of the system in a variety of ways, depending on system voltage level and the load density. The three main topologies used to design distribution networks, are illustrated in Figure 2:

1. radial
2. ring / weakly-meshed
3. meshed

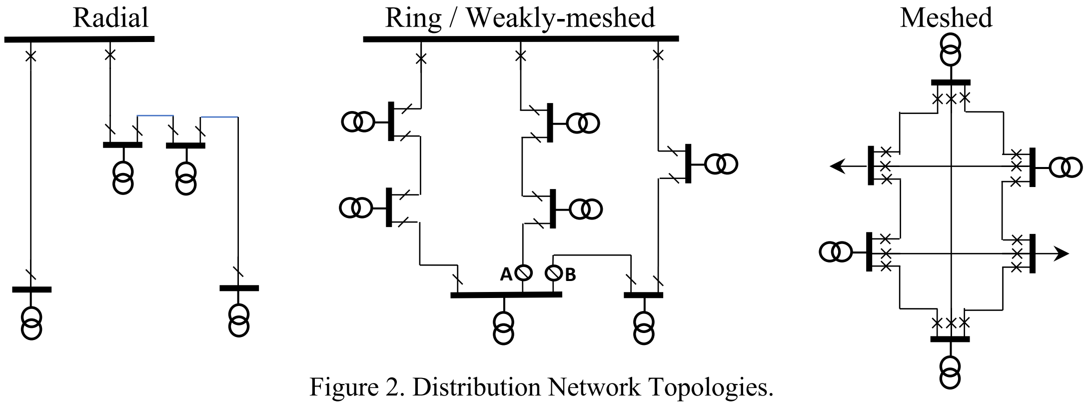

Figure 2. Distribution Network Topologies.

In a radial network, each node is connected to the substation via one path only. Typically, the radial network topology is used in LV distribution networks and in MV long rural lines that connect isolated load areas. The ring topology (with radial operation, by keeping the redundant branches open, to simplify the protection schemes) is adopted in most MV feeders to improve the security of the supply in the event of circuit outages during faults or scheduled outages due to maintenance. Indeed, the Normal Open Point (NOP) is located between the two interconnected feeders (A and B in Figure 2) to ensure radial operation for each feeder. The location of the NOP can be moved following the occurrence of a fault, such that the faulty section is isolated and power is restored to all users connected to the two interconnected feeders. Sometimes, distribution feeders serving high-density load areas (e.g., urban areas) could contain few loops created by closing NOP switches. Rings and weakly mesh systems may be operated split with normally open points, or closed to improve security, although the latter solution requires more circuit breakers and more sophisticated protection.

Greater security could be achieved by meshed topology. The connection of multiple substations in parallel can reduce the total transformer capacity into the group. Such an arrangement can accept the loss of one in-feed without interruption of supplies within the network, if subject to satisfactory network circuit loadings (Lakervi & Holmes 2007). However, parallel operation of the laced points can result in reverse power flows through the in-feed transformers under outage conditions on the higher voltage system: care must be taken that the fault levels within the network are acceptable. The meshed topology is adopted at the HV level, due to the large distribution areas (regional networks). Depending on the regulation in place in various jurisdictions, HV regional networks can be managed by the DSO or by the TSO.

In the last decades, the fast changing nature of the end-user loads and distributed RES, the smart grid concept has been developed as illustrated in Figure 3, with the addition of DG, DS, and an information infrastructure that goes beyond the traditional system control and data acquisition and energy management systems. In the smart grid scenario, generation will largely shift from centralised transmission systems to decentralised connected distribution system generation. The connection of additional energy sources into existing distribution systems leads to a series of technical troubles, such as possible inversion of power flows, possible overvoltages, modification of short-circuit currents, stability problems, among others (Barker & De Mello 2000; Ochoa et al. 2006; Muhanji et al. 2018).

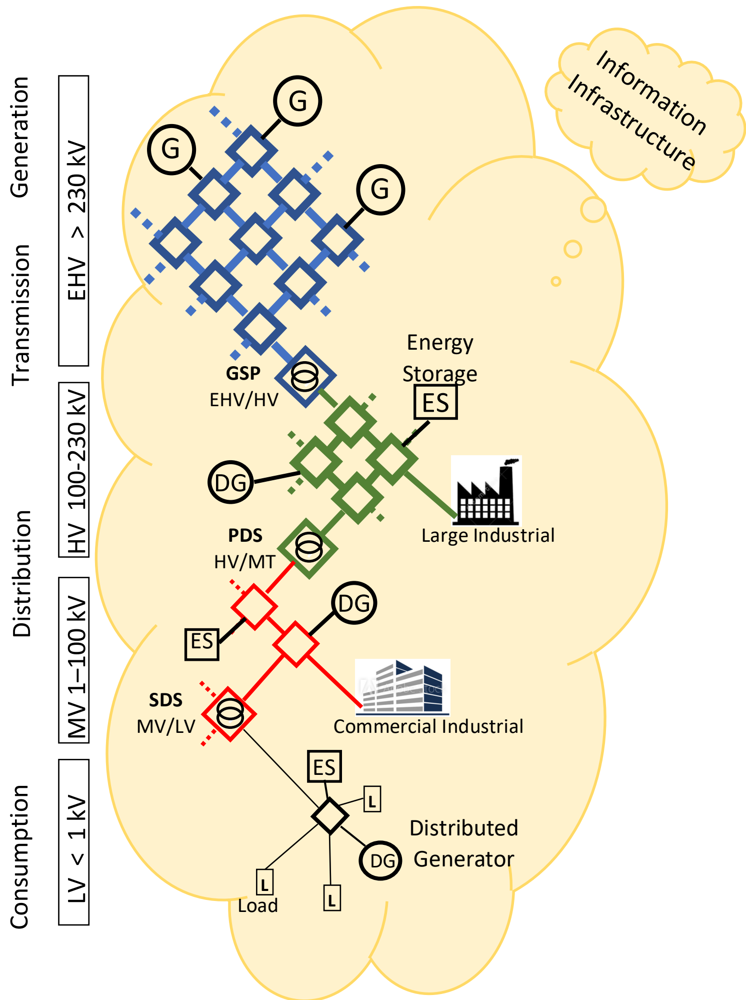

Figure 3. From conventional structure to Smart Grid concept.

1.3.2. Microgrids, Nanogrids and Picogrids

Due to the challenges of integrating DER in the distribution systems, a decentralised control concept is emerging to solve local problems and address fundamental changes in future grids.

Microgrids (MGs) are one way for providing that decentralisation of the generation resources (Lasseter 2001). There are many definitions of MG, most of which agree with some aspects that MGs may share. A MG can be defined as a cluster of micro-generators, ES, and loads, that operates as a single system (Lasseter et al. 2002), with clearly defined boundaries, with island capabilities. The MG can be connected or not to a main grid through a Point of Common Coupling (PCC) (IEEE Power and Energy Society 2017; CIGRÉ 2015). A MG can operate independently from the grid in "island" mode or connected to it (Parhizi et al. 2015). When the MG has a connection to the main power grid, all power deficit or surplus can be absorbed or delivered to the power grid. On the other hand, the balance must be satisfied locally by the MG itself, if it is autonomous or if it is operating in island mode.

As a natural extension of the MG concept (Martin-Martínez et al. 2016), two less used concepts to configure a new hierarchical scheme are:

- *Nanogrid* (NG) can be defined as the grid of a building with DER and DS systems.
- *Picogrid* (PG) can be defined as an aggregation of the manageable loads connected in a household.

This hierarchical approach encompasses all the chain from households up to the distribution networks. In other words, PGs, NGs and MGs are the electricity grids which usually correspond to households, buildings and neighbourhoods respectively, and which are finally connected to the power distribution grid or to another MG.

PGs objectives are to carry out load management to minimise energy purchase costs (e.g., peak-shaving, load-shifting by price signals) and to execute orders resulting from the NG. Therefore, PGs do not include generation systems. These management systems could belong to an energy service provider (ESP) or an aggregator.

NGs not only use energy management algorithms in order to manage their loads, but also try to maximise DER integration. Thus, NGs are in charge of controlling local generation (e.g., small wind turbines and small photovoltaic generators), loads and PGs. NGs may also include DS (e.g., batteries from EVs). NGs could use building management system (BMS) from an ESP or aggregator/retailer to carry out their services.

MGs control NGs and micro-generation (micro-wind turbines, biomass boilers, Combined Heating, Cooling and Power – CHCP). MGs may be either connected to the electricity distribution network, or connected to another MG. Therefore, the main functions of MGs are to maximise DER integration and to assure isolated operation of the system when required. Thus, there will be two systems in this network: a MG Management System (MGMS) hosted by the DSO to guarantee stability and security in the network and an Aggregated Management System owned by an ESP or aggregator to manage the energy and economic exchanges of the MG and provide energy efficiency services.

1.3.3. Multi-microgrids and Web of Cells

In the development from MG to smart grid, the new challenge becomes how to coordinate efficient and reliable operation of multiple sub-MGs. With more MGs interconnected to the power grid, the neighbouring MGs in a certain region form a multi-microgrid (MMG) system.

It is possible to classify MMGs from many technical aspects such as voltage level, AC/DC constitutional forms, phase-sequence constitutional forms, and functional aspects such as remote-area type, residential-area type, office-building type, industrial-park type. The optimal operation of MMGs is the core and hot issue of MMGs, which mainly includes islanded optimal operation and grid-connected optimal operation (Xu et al. 2018):

1) Islanded optimal operation of MMGs: the big difference with single MG is that MMGs can achieve optimal operation when off-grid through rationally allocating the idle resources of each sub-MG. In fact, continuous optimisation requires a combination of source/load power forecasting, and arranges the charge/discharge plan of ESS and switching of load based on the actual MMG operation states, to extend the running time of MMGs.
2) Grid-connected optimal operation of MMGs: different from grid-connected operation control of single MG, MMGs can use a sub-MG as a decision-making individual to achieve the overall efficiency. Considering uncertainties in both RES and forecast electric loads, Hussain et al. (2016) proposed a robust optimisation-based scheduling strategy to reduce the operation cost of MMGs system in grid-connected mode. Through the combination of source/load power forecasting, an optimal operation model can be established by considering the generation capacity of DGs, information of electricity price, load expectation of users, comfort, and other factors (Zeng et al. 2013).

Web-of-Cells (WoC, Martini et al. 2015) is a decentralised control scheme proposed to manage the power flow deviations of the local inter-cell connection line rather than the system frequency. The task of detecting and correcting these deviations in real time is delegated to the local operators. This results in less computational complexity and less communication. To limit the number of reserve activations, a peer-to-peer intercellular coordination mechanism has been proposed to obtain a compensation result of the localised imbalance. Local voltage problems will increase, and a local cell operator will have to handle them, due to their local nature. This opens up opportunities for more active voltage control, where local optimal set-points are repeatedly determined based on updated local information and forecasts.

1.4 Renewable Energy Sources

The development of ADNs includes the appropriate grid integration of the main RES, which nowadays are the solar energy by means of the PhotoVoltaic (PV) generators, and the wind energy by means of the Wind Turbines (WT).

In an electric power system, the grid integration of intrinsically intermittent power production means that a large amount of power generation (up to the majority of the total), with respect to the global power consumption, shall not create worsening, from both short-term and long-term perspectives, in the two fundamental tasks of the TSOs and the DSOs, that is:

- the stability of the common frequency in the voltage and current waveforms;
- the stability of the amplitude or root mean square (RMS) values of the voltage waveforms at the various voltage levels (HV, MV, and LV) in the networks.

The tasks can be accomplished by the so-called controls of *active power and frequency* (with adjustment at the global level) and *reactive power and voltage* (with adjustment down to the local level) (Weedy et al. 2012).

Concerning the frequency stability, the global balance of the electric power systems between generation and consumption, including the power losses in the transmission lines, is achieved in real time, using the spinning reserves, under the control of the TSOs. They obtain this equilibrium by activating reserves according to the primary, secondary and tertiary controls, respectively with increasing time constants (UCTE 2004; ENTSOE 2013).

Regarding a generation unit (centralised power station) involved in the control of active power and frequency, the local regulation consists of a speed droop characteristic by means of the speed governor. It is an analytical relationship (usually linear) between the speed of the synchronous generator (linked to the electric frequency) and the active power generated by the unit (Weedy et al. 2012). This curve provides the amount of speed reduction, as the required power is increased, starting from the no-load speed that corresponds to a frequency higher than the rated frequency of the grid.

On the other hand, the control of *reactive power and voltage* can be managed not only at HV by synchronous compensators but also at the MV and LV levels by capacitors or static var compensators. Therefore, intermittent RES like PV plants and WT parks can certainly participate to achieve the stability of the network voltage. In this sense, both active power and reactive power of users, at the end of the distribution lines, with their own sign, can cause either a voltage rise or a voltage drop over the distribution transformers and lines. As a voltage drop corresponds to a passive user that consumes both active power and reactive power (inductive behaviour), a voltage rise corresponds to an active user that produces both active power and reactive power (capacitive behaviour). Opposite signs of active power and reactive power of the users determine a compensation, with consequent reduction of the voltage perturbation.

Recently, on a national basis some TSOs have published technical specifications, for DG and in particular for PV plants, which provide rules regarding the following items during possible transient evolutions of frequency and voltage amplitudes:

- regulations of active power as a function of power frequency to reduce the generated power in the case of transient over-frequency event;
- regulations (both local and centralised ones) of reactive power with both capacitive and inductive behaviours, to counteract the transient under-voltage and over-voltage events.

In the sequel of this section, *five* specific subjects addressing the typical technical aspects of grid integration regarding the PV generators and wind turbines are presented.

The *power quality* of LV grids in case of PV generators, with rated power of some hundreds of kilowatts in normal operation and under partial shading of their PV modules, is investigated in Spertino et al. (2012), to provide details about the development of a new grid code in Italy to take into account the remarkable weight of PV and WT systems with intermittent production. This article discusses the power quality of LV grids in case of PV generators with rated power of some hundreds of kilowatts in normal operation and under partial shading of their PV modules. For real three-phase systems, the harmonic content of the current waveforms injected into the grid and the corresponding grid voltage waveforms, together with the unbalance and power factor evolutions, is assessed by extensive measurements from an experimental campaign. The results demonstrate that the harmonic content, the unbalance, and the power factor of PV generation do not create issues at the point of common coupling.

Unbalance of the three-phase currents in building-integrated PV systems may concern structural aspects of the installation, the effect of partial shading, or both. In Chicco et al. (2014), specific unbalance indicators are given on the basis of measurements on a large building-integrated PV system that includes different types of unbalance. The values of indicators distinguish the balance and unbalance components that are affected by waveform distortion. These indices extend the usual definitions of unbalance, well-known from the power quality standards. The results show that the unbalance cannot be considered negligible, even with no single-phase inverter, and it is more significant if non-linear loads add a contribution to both harmonic distortion and unbalance from the viewpoint of the distribution transformer.

Considering *voltage control,* the centralised and distributed solutions at the LV level in the presence of strong PV generation are compared in Ciocia et al. (2019). The centralised devices under study are static var compensators and on load tap changers of MV-LV distribution transformers. The distributed devices are the grid-connected inverters for coupling the PV generators at LV level. An appropriate control of the inverters, proposed by managing their reactive power, permits to maintain the voltage fluctuations within prefixed limits over the distribution lines without an expensive investment on centralised devices at the MV-LV substation level. The simulation results show how the centralised and the distributed *voltage controls* interact over the length of the distribution lines.

From the viewpoint of *intermittent RES*, the joint production of PV and WT systems with electrochemical batteries is addressed for power stabilisation in Spertino et al. (2017a). Starting from the estimation of the availability of the solar resource and wind resource for two sites in southern Italy, it is found that the global availability of the RES exceeds two thirds of the yearly hours. Then, to exploit this availability of at least one of the two resources, particularly the solar energy, the best type of load pattern is represented by the tertiary sector loads, as for example the commercial loads (in the specific case, communication companies). The capacities of the generation and the storage are determined in such a way as to minimise the power injection into the public grid, and to maximise the self-sufficiency of the users.

Considering a future perspective, the *planning* of PV and WT power is performed in Spertino et al. (2017b) with a simulation procedure to meet the consumption of aggregate users. The planning procedure is applied with the usage of batteries for large areas of sunny and windy regions (for instance the Mediterranean zone), taking into account not only the costs of investment, operation and maintenance, but also the revenues from the energy savings. The sites studied are five, located in Southern Italy, with mutual distances exceeding one hundred kilometers, while the solar resource and the wind resource are accurately measured by meteorological stations. The results are presented with respect to two objectives, namely, the maximisation of the electrical self-sufficiency for the aggregated users, and the optimal solution from the point of view of the economic investment.

1.5. Energy Conversion

In the energy conversion scenario, power electronics is an enabling technology. In recent years, power electronics applications continuously gained importance in the field of RES, electrical distribution systems and MGs. Moreover, many applications such as in the field of traction, data centres or telecommunication systems, use power systems with batteries and/or fuel cells to store energy and supply the required loads. In all these technical areas, power converters and related electronic switches have allowed a paradigm shift in the development and performance behaviour, improving power and energy systems. Remarkable advantages arise in the power converters extensive use, due to the increased availability of several converter topologies and power switches technologies choices, growing in the last decade. The improved converter switching capability and the feasibility of a suitable and redundant converter design allow advances in the dynamic performance, with extended operating range, reduced line harmonics, and adjustable power factor parameter.

1.5.1. Power Electronic Switches for Grid Applications

Silicon-based high-voltage semiconductor devices play the crucial role of switches applications in the conversion of high-power electronics (megawatt until gigawatt applications). The areas of use are related to traction drives, industrial applications, grid and microgrid systems. Instead, in lower power applications the wide bandgap (WBG) components, Silicon Carbide (SiC) and Gallium Nitride (GaN) are the next generation switches for high-performance power conversion. These high-performance devices are gradually replacing pure silicon Insulated Gate Bipolar Transistors (IGBTs) and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) in different power electronics applications. The technology-developing trend leads that SiCs and GaN will be increasingly present in high power and high voltage applications in the next years. For very high-power applications such as the electrical power transmission, the Phase-Controlled Thyristor (PCT) is the electronic bipolar switch mainly used (Vobecký et al. 2017). The PCT is applied mainly in controlled rectifiers and inverters. The PCT in the series connection is implemented in very high voltage converter or circuit breaker applications (hundreds of kV). Triggering the gate terminal can turn on these devices. The turn-off transient is obtained by natural commutation in AC converter circuit and forced commutation way in DC applications (Lips 1998). The Integrated Gate Commutated Thyristor (IGCT) and Injection Enhanced Gate Transistor (IEGT) are based on Gate Turn-off Thyristor (GTO) technology and allow turn-off and turn-on capability by the gate triggering (Vobecký et al. 2017). The switching frequency is in the range of 100 Hz to few kHz. The bipolar gate-controlled devices applications are in the field of hundreds of megawatts. The IGBT is a flexible device with low-voltage and low-power gate-controlled switching transients (Wang & Ma 2016). The switching transients from a few kHz to one hundred kHz in the case of very speed low power devices. The IGBTs are mainly applied in medium and high-power converter topology. The breakdown voltage is up to 6 kV. In this high voltage switching scenario, it is important to not forget the power diode contribution, which covers the whole power range for rectification, snubber or freewheeling purposes.

The SiC devices feature high-switching performance and very favourable temperature behaviour (Musumeci 2015; Ji et al. 2017). The SiC devices are the best competitors for the super-junction silicon MOSFET in their applications. Furthermore, the SiC technology today is getting closer and closer to the areas of application of IGBTs and is increasingly replacing it in applications such as battery chargers and converters for the automotive sector (Ji et al. 2017). The GaN devices were born for the wireless and high-frequency electronic system applications. In recent years, the high switching performance is bringing the device to be used above all for low voltage applications (< 100 V) where the size of the electronic converter systems need to be optimised. The trend of growth of the GaN breakdown voltage and power management capability is high; consequently, the WBG switch in the next years will be more and more competitive with SiC devices (Kanechika et al. 2010).

1.5.2. Power Converter Topology for High Voltage Applications

The electrical energy is used in industrial, transportation, commercial and residential applications. In several uses, the electrical quantities need to be converted by suitable converter circuits in an appropriate electrical form, from AC to DC (AC/DC) or vice versa (DC/AC). The DC or AC voltage and current need to be controlled and regulated, from which there are DC/DC and AC/AC converters topologies. The range of energy conversion covers a few tens or hundreds of watts until tens of GW.

In medium and high-voltage applications, power electronics have a growing importance for industrial and traction applications as well as RES and power transmission. Several converter topologies are developed based on the conversion form need and power level rate. In the power transmission environment, the flexible alternating current transmission systems (FACTS) and high voltage direct current (HVDC) transmission use different power semiconductor-based circuit topologies such as Current Source Converters (CSC) and Voltage Source Converters (VSC). The power devices used in the converter topologies, employed for the DC/AC or AC/DC conversion process depending mainly on the transmission distance and power levels involved. Generally, the PCT devices in series connections are used in applications with very high-power demands such as cycloconverters, grid-commutated converters, or load-commutated converters (Ludois & Venkataramanan 2010). Furthermore, CSC uses PCT because it is a kind of Line Commutated Converter (LCC) and the PCT is switched off when the current through it crosses zero, therefore, it requires line voltage for commutation. For long distances transmission equipment, CSC topologies are widely preferred due to their overall low system losses. In high-voltage industrial application, the pulse width modulation (PWM) current source inverter is applied to overcome the LCC drawback such as low-input power factor and distorted input current waveforms. In PWM controlled converter the VSC is predominant on the CSC solution (Ludois & Venkataramanan 2010). With the advances in the technologies of the gate-controlled semiconductor switches, the VSC has become the cornerstone for industrial power conversion, while increasingly emerging as a viable option for HVDC applications. The VSC solution is mainly used at short transmission distances. In PWM VSC topologies the power switching devices are driven by a modulated square wave control signal. The capability of the device to be switched on and off as quickly as possible is very important for the converter dynamic performance, whereby devices from the GTO family or more performant IGBTs can be chosen over PCTs based on the required power level.

A series connection of semiconductor power electronic switches does not improve the power quality of the AC waveforms and is increasingly complex to implement, as the number of devices to be connected in series increases according to the voltage required by the electrical bus. The main issue is the different distribution of the voltage on the series-connected devices due to the unequal static and dynamic characteristics of the semiconductor components. The correct sharing of the static and dynamic devices blocking voltage is obtained with an additional circuit that increases the power losses and lowers the system reliability.

The multilevel power converter topologies are a viable solution to these drawbacks. The multilevel converters are an evolution of the two-level converter concept. In the multilevel solution, the power semiconductor switches are not connected directly in series. Modular Multilevel Converters (MMCs) are based on an identical basic cell, replicated n-times and interconnected with a few other components, usually diodes and capacitors, until the specific structure of the converter is obtained. The output of the MMC is a step stepped waveform voltage, which depends on the converter levels. The switching of the power devices allows the addition of the capacitor voltages, which reach high voltages at the output, while the power semiconductors have to withstand only reduced voltages (Abu-Rab et al. 2010). The MMCs are useful for the possibility of splitting the total voltage of the DC-link on several active devices. In this way, they can withstand very high voltages (hundreds of kilovolts) contributing overall to drive loads of extreme power (hundreds of megawatts). Furthermore, in a multilevel converter, the availability of different voltage steps allows to more accurately emulate the trend of a sinusoidal voltage. For this reason, the harmonic level that can be calculated according to the Fourier analysis is naturally more contained in the multilevel reconstruction than the only two square wave levels (obtained in the two-level inverter). This results in a reduced Total Harmonic Distortion (THD). The THD decreases the more the voltage steps are numerous, increasing the power quality. In Figure 4 the evolution concept of the multilevel solution is shown (Rodriguez et al. 2009). In Figure 4a the two-level switching pole is reported with the output voltage waveform, while in Figure 4b there is the principle of the three-level switching pole with the improved output waveform quality. Finally, in Figure 4c the concept of multilevel switching pole is generalised for *n* levels. The output voltage of Figure 4c is related to 9-levels converter, the output voltage THD, in this case, is even more reduced than in the previous case.

In the area of the MMCs for high voltage inverter applications, mainly three multilevel topologies have been developed:

- diode-clamped (or Neutral Point Clamped - NPC);
- capacitor-clamped (flying capacitors - FLC);

- cascaded multicell with separate DC sources.

The NPC multilevel converter is composed of a stack based-on the switching pole (inverter leg) typical of two-level VSCs (Figure 5a) arranged with a suitable clamping diodes connection to obtain the output step voltage. The three-level TPC topology switching pole of a single-phase VSC is depicted in Figure 5b. The number of clamping diodes needed to share the voltage increases dramatically with the growth of the number of converter levels. For this reason, together with the increasing difficulty to control the dc-link capacitor unbalance, the industrial applications with TPC arrangement are mainly oriented on the three-levels converters.

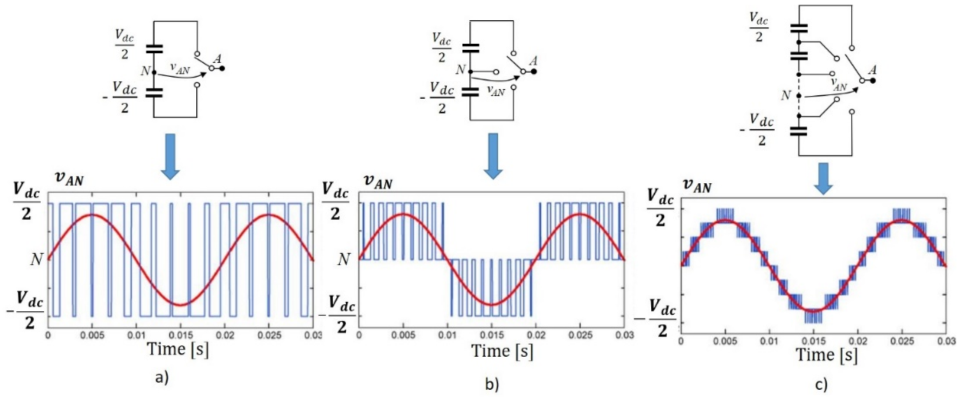

Figure 4. Multilevel principle and output waveforms: a) two-level switching pole, b) three-level switching pole, c) *n*-level switching pole and output waveforms with *n*=9 (Rodriguez et al. 2009).

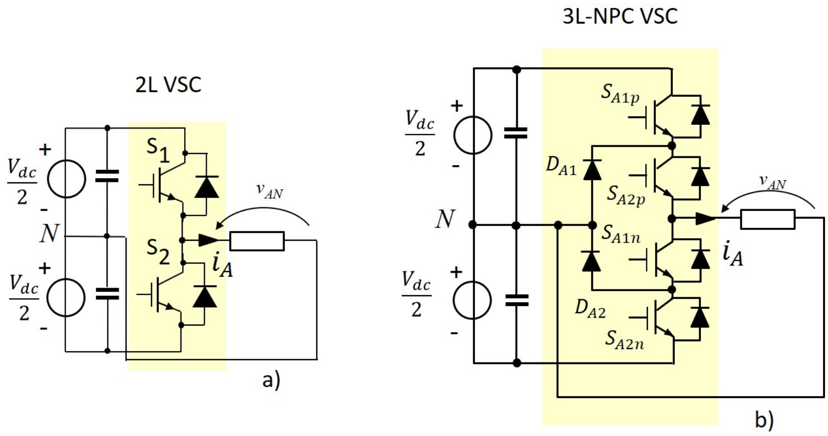

Figure 5. a) Two level VSC inverter leg switching pole, b) Three-level TPC topology switching pole for a single-phase VSC.

The FLC topology is quite resembling the NPC converter. In FLC arrangement, the clamping diodes are replaced by flying capacitors. The most important difference with the NPC topology is that the FLC has a simpler modular structure, and it can be more easily extended to achieve high voltage multilevel converter (Rodriguez et al. 2009). In higher voltage applications, to increase the output voltage the multilevel solutions, the single switch of one leg of the switching pole is also made with two or three devices in series connection.

NPC and FCC inverters have some difficulty relating to the management of high voltage capacitors and their voltage balancing. For this reason, other topologies have been investigated. The topology of multilevel converters based on serial single-phase converters (H-bridge) is a useful converter structure without the capacitors management drawback.

The Cascaded H-Bridge (CHB) converters with separate DC sources are multilevel converters composed of the series connection of two or more single-phase H-bridge inverters, hence the name. The CHB converters are capable to reach both higher voltage and power levels, but the converter topology requires a large number of isolated DC links. Every isolated DC link is achieved by a suitable isolated secondary path of a transformer with a rectifier circuit. Furthermore, the several H-bridges allow operation of the converter at lower switching frequencies and also facilitate loss distribution among all the power devices. Other multilevel promising topologies based on 3L T-Type Converter Topology or matrix converter have appeared in recent years, but industrial use is currently not very extensive (Wang et al. 2017). Furthermore, hybrid multilevel converters have been investigated to mix the best features of various topologies (Zhang et al. 2019). A classification of the various power converter topologies for high voltage is reported in Figure 6. To control the output waveforms in addition to the listed topologies, several modulation strategies have been developed to optimise the performance of the multilevel converters, such as multilevel sinusoidal PWM, multilevel selective harmonic elimination, and space-vector modulation (Rodriguez et al. 2009).

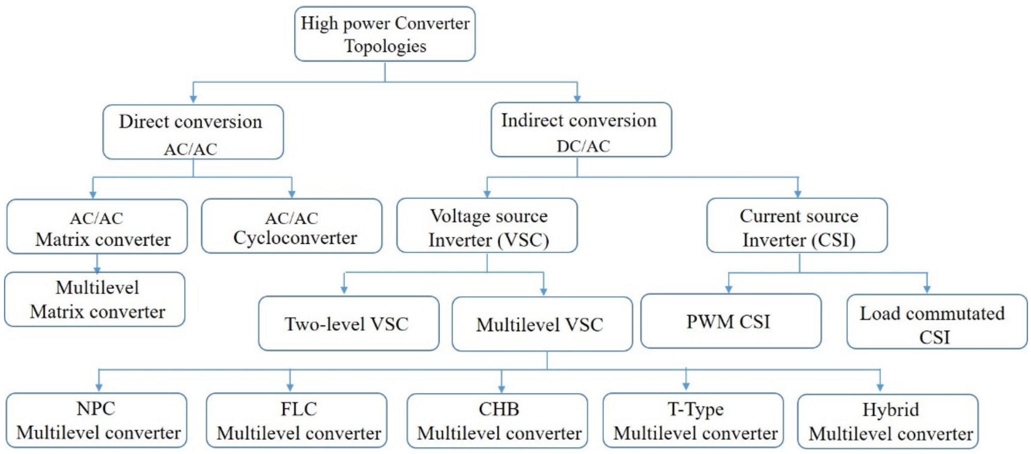

Figure 6. Classification of power converter for high-voltage applications.

1.5.3. Converter Topologies in Microgrid Applications

In a MG, numerous power converters are involved to integrate DER (i.e. micro-generators), energy storage devices (e.g. batteries, flywheels, super-capacitors, fuel-cell), and critical or flexible loads. In a MG, the whole resources and load interface are managed by a suitable control system. The control system manages the fault conditions disconnecting the MG from the utility network as fast as possible (Kumar et al. 2017). MGs are generally interconnected to LV or MV utility grid by a direct connection or through an interfacing power converter. A basic network structure of an AC MG and its main components is shown in Figure 7. The RES (wind and photovoltaic) are connected by a controlled rectifier circuit and an inverter to control the frequency and the voltage level at the AC network. A controlled AC/DC converter with a suitable power factor corrector are arranged to connect the EV battery charging station. The energy storage useful to obtain dispatchable sources is connected via a DC/AC converter to the AC main. The Industrial AC load needs a suitable AC/DC/AC conversion to control both the frequency and the power level to drive the AC motor. Furthermore, the AC loads in the residential home need several suitable power supplies.

The dynamic characteristics of the power converter allow improving the control of the specific load and the quality of the AC waveforms in the grid as well as the Electromagnetic Interference (EMI) content. In this direction, in recent years, the power converter has been used in the AC network to improve the power quality by a virtual synchronous generator (Mandrile et al. 2020). Traditional electromagnetic transformers are also beginning to be replaced with solid-state transformers (SSTs) achieved through an AC/AC conversion circuits composed for example of two H-bridges with bidirectional devices, galvanically separated by a much smaller high-frequency transformer compared to a corresponding low-frequency electromagnetic transformer. The SST disadvantage (increasing complexity) is offset by the flexibility of the electrical quantities management and the possibility of full control that allows MG to be made increasingly smart and safety (Huber & Kolar 2019). In DC MGs the power converters involved are shown in Figure 8. In the DC network, the number of power converters is optimised. From Figure 8, for example, it arises that the level three charging station and the energy storage system are interfaced through directly with a DC/DC converter to regulate both the voltage and current to the main DC link. Finally, the AC protection switches in the AC MGs are replaced by a further power converter (DC/AC) to allow and control the interconnection with the AC grid.

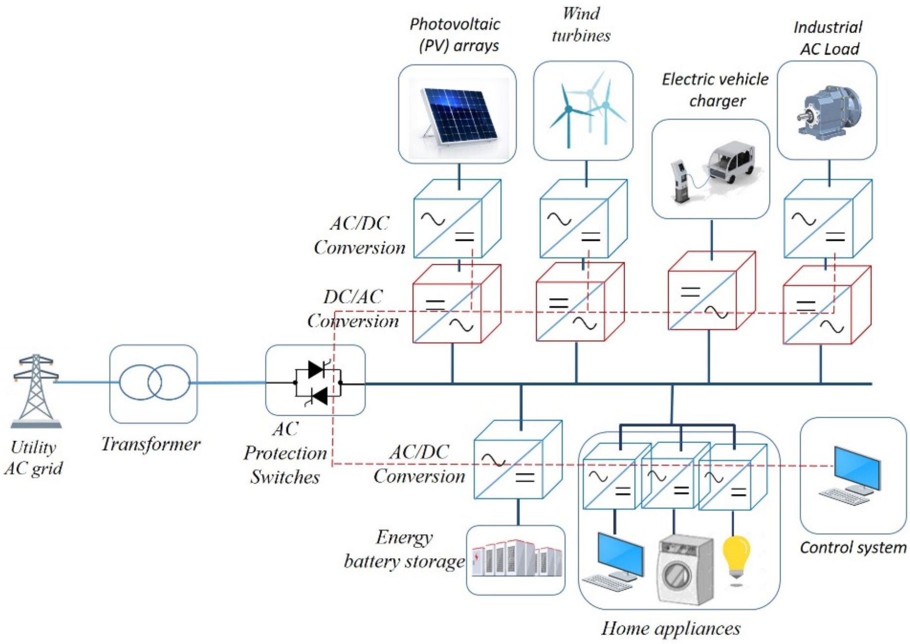

Figure 7. AC microgrids and main power converter involved in the energy conversion.

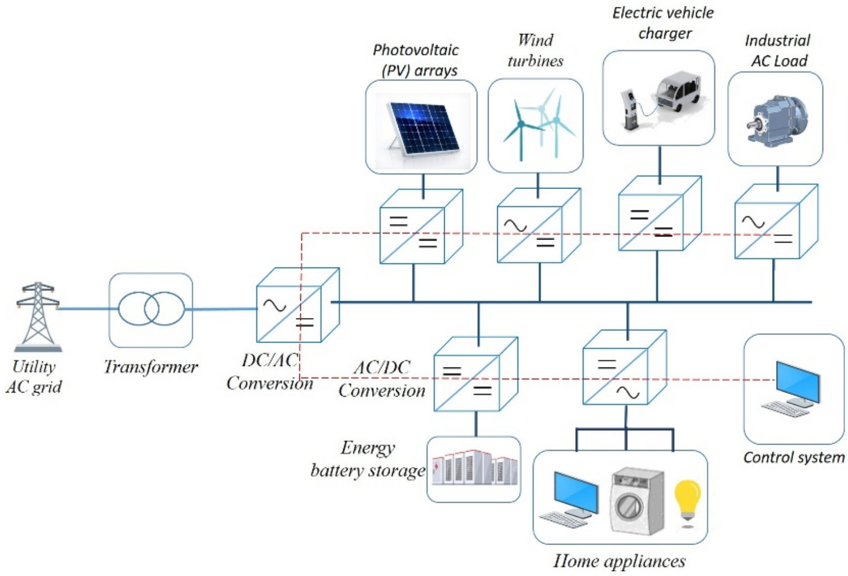

Figure 8. DC microgrids and main power converter involved in the energy conversion.

1.6. Operational Aspects

From the operational point of view, in ADNs some interesting aspects are gaining more attention in the recent years. In particular, the concept of Virtual Power Plant (VPP), the network optimisation, the supports to frequency and voltage control, and stability. In the next paragraphs, these four main aspects are briefly discussed.

1.6.1. Virtual Power Plants

Nowadays, significant changes in the way energy is generated can be observed. For example, the production from RES is significantly increasing due to the ambitious decarbonisation programmes imposed by governments to reduce the global warming, and due to the technological evolution. Moreover, thanks also to the energy market liberalisation, large generation power plants are being replaced by small distributed generators. Due to these changes, the electrical networks and the operational strategies of both DSOs and TSOs are, in turn, changing, with the aim of dispatching electrical energy with high quality standards.

From a technical point of view, this evolution is made necessary by the intermittent nature of some resources, such as wind and solar, which causes uncertainty in the electrical energy production. To face this problem, an innovative solution was proposed in 1997: the Virtual Power Plants (VPPs) (Pudjianto et al. 2007; Awerbuch & Preston 2012). The idea consists of grouping together various small size DERs, including for example small size distributed power plants, RES, storage, controllable loads and EVs. Within a certain VPP, DERs can lay in large geographical areas (Nosratabadi et al. 2017). The DERs are then managed by an energy management system (Kasaei et al. 2017). Basically, the activities of this energy management system can be summarised in three steps. Firstly, it receives as inputs data about the actual productions and signals from the market at a certain time. Secondly, it forecasts the values of uncertain parameters, such as for example the renewable output power and the load demand (Yu et al. 2019, Nosratabadi et al. 2017). Thirdly, it coordinates the interconnected RES to maximise its objective function; in fact, optimal generation schedules for the management of a DER portfolio can be formulated by considering several objectives, such as the reduction of the internal operating cost structure or the maximisation of the profits (Nosratabadi et al. 2017). In the optimisation problem, both the technical and the economical specifications of the system components can be considered.

From an external point of view, VPPs act as a conventional transmission connected power plant, and therefore are characterised by parameters such as scheduled output, ramp rates and voltage regulation capability (Pudijanto et al. 2007). Important examples of VPPs are already developed in Germany and UK, where thousands of units are interconnected together.

In conclusion, VPPs facilitate DER trading in the wholesale energy markets and can provide services to support transmission system management (e.g., various types of reserves, frequency and voltage regulation).

1.6.2. Optimisation

Optimisation is mainly related to the network configuration and to the DG dispatch in the operation phase, and to network reinforcement and DG placement in a planning phase.

ADNs can be active in terms of real-time optimisation of the network topology, the so-called network reconfiguration. Different optimisation objectives have been proposed in the literature, such as reducing network losses, improving the voltage profiles, load balancing, reducing service interruptions and therefore improving reliability indices, minimising fault currents, maximising local consumption of renewable energy, etc., or reconfiguration can be performed for service restoration after a fault. In addition, different optimisation algorithms have been proposed, based for example on simulated annealing, linear programming or heuristic techniques, tabu search, fuzzy reasoning approaches, genetic algorithms, vector immune systems, ant-colony, etc. Researchers often study multi-objective optimisation, usually based on the Pareto optimality criterion. In order to be able to perform ADN optimisation and reconfiguration, real-time data from the DN should be available, provided by an Advanced Metering System supported by a proper data management infrastructure (Paterakis et al. 2015, Pau et al. 2018).

A second aspect of ADN optimisation is active dispatching of DGs. An optimised dispatch of DGs could significantly improve the acceptance of a large level of DER, mostly of the renewable type, into distribution grids (Borghetti et al. 2010).

A different aspect of ADN optimisation is the planning stage. Many researchers worked on active distribution systems expansion planning, e.g., rewiring, non-real-time network reconfiguration, installation of new protection devices, etc. In this case, it is extremely important to take uncertainties of loads and generation into account (Martins & Borges 2011; Ehsan & Yang 2019), typically with scenario studies to represent the variability of the possible uncertainties on different parameters.

1.6.3. Frequency and Voltage Control, and Stability Issues

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subject to a physical disturbance, with most system variables bounded so that practically the entire system remains intact (Kundur et al. 2003). TSOs and DSOs shall ensure frequency and voltage stability. These tasks can be accomplished by the so-called "control of active power and frequency" and "control of reactive power and voltage".

In electrical networks, the active power has to be generated at the same time it is consumed. Disturbances in this balance, causing a deviation of the system frequency from its set-point values, is offset initially by the kinetic energy of the rotating generating sets and motors connected. Later, primary controllers of the regulating units respond within few seconds, increasing or decreasing (according to the sign of the frequency deviation) the power delivered. Thanks to primary controllers, the balance between demand and generation is re-established, and consequently the frequency stabilises and remains at a quasi-steady-state value, even if it differs from the set-point. To restore the original frequency and the original power exchanges to their programmed set-point values, the secondary controller reacts in some tens of seconds. TSOs draw resources from primary, secondary and tertiary control reserves, which are pre-allocated powers dedicated to keep the frequency at the desired set-point (UCTE 2004). All the power units with rated capacity greater than a specific threshold (e.g., 10 MW in Italy) shall contribute to the primary control reserve. Only those that are fed by non-programmable renewable sources do not contribute (Terna 2008).

ADNs, if not correctly operated and controlled, can create problems in terms of voltage and frequency stability to the bulk power system. On the contrary, if properly controlled and operated, ADN can provide support to the frequency and voltage stability of the bulk power system. ADNs, in certain cases, may also operate in islanded mode. In this specific situation they should be controlled in order to guarantee the island voltage and frequency stability.

Frequency stability is a critical aspect especially in islanded ADNs. In the bulk power system, frequency stability is dominated by governors' responses. Frequency stability has been studied in "small" islanded power systems, for example in (Horne et al. 2004), considering as small a portion of the transmission network. However, in ADNs with high shares of RES, the problem of islanded operation is still to be studied in depth.

In ADNs the DGs and ES connected to the grid through VSCs may in the future provide support for frequency stability thanks to synthetic inertia and fast frequency responses, especially in low inertia power systems (Eriksson 2017). These are quite popular topics, being studied by researchers worldwide.

In a scenario with high RES penetration, frequency instability is a concrete risk for two reasons: firstly, the inertia of the system is lower; secondly, the primary control reserve is reduced. Moreover, in this kind of scenario, TSOs could need larger secondary and tertiary control reserves to stabilise the frequency, which means extra costs to find these services. RES power plants with high capacity can help the system in the frequency control thanks to the so-called *synthetic inertia*, which is the controlled response from a generating unit to mimic the exchange of rotational energy from a synchronous machine with the power system (Eriksson et al. 2017). A different instrument that can contribute to stabilise the frequency is DR (Doudna 2001): prosumers change their load/production to receive economic benefits. DR is a strategy that will have more and more importance in the next future, thanks also to the development of smart grid technology, controllable loads and DG (Nan et al. 2018). In order to exploit numerous small energy resources, such as household appliances, aggregators are required; their tasks are to trade on the ancillary service market and to coordinate all the resources (Giovanelli et al. 2018).

DERs can also have an impact on the voltage profile, determining voltages at certain nodes of the network that cannot be tolerate. Traditionally, voltage control is performed through the load tap changers of HV/MV transformers, in order to increase and decrease the turn ratio to compensate voltage drop along the feeders; power factor capacitor banks and static var compensators are equipment that can contribute to control the voltage profile as well. In case of a distribution network with DERs, this strategy could not be enough. This occurs when the power injected by local generators may cause an unacceptable voltage rise at one or more nodes, while the power withdrawn at load nodes causes an unacceptable voltage drop at these nodes. The probability of this scenario increases in case of long feeders and high injected/withdrawal power. To overcome these issues, innovative strategies shall be adopted, such as for example the decentralisation of voltage control, which however has to be coordinated to avoid the negative effects of independent decisions on the voltage profiles.

One of the key points related to voltage stability is voltage control and reactive power support, which could be provided in an active distribution grids, in addition to traditional controls from synchronous machines, by VSC-interfaced DGs (Majumder 2013, Ciocia et al. 2019). For this purpose, different control strategies could be applied, resorting to centralised or distributed control, both having advantages and disadvantages. A good compromise could in fact be a double layer hierarchical control, with a high level centralised control and a low level distributed control with the possibility of working autonomously in case of failure of the centralised control and communication system.

An important issue related to voltage stability is the interaction between transmission system and ADNs, especially in stressed network operating conditions. In case VSCs and DGs are not properly controlled in the distribution network, their behaviour may undermine the voltage control actions (e.g., tap changes) operated in the transmission system or at the HV/MV substation (Aristidou et al. 2015).

1.7. Economic Aspects

The significant presence of DERs in an ADN poses also problems related to the economic aspects. Indeed, when integrating responsive loads, DERs as well as prosumers in a distribution network, the economic framework is expected to change from a centralised approach to a distributed approach. One aspect which has been recognised as one of the most important is the novel approach to the *trading*, while an issue that accompanies this transformation is the determination of value-based signals together with the determination of adequate price signals to promote the participation of DERs into several operational problems of ADNs.

Along with the transition of distribution networks in ADNs, it arises the necessity of a transition of the energy markets in order to exploit the opportunities provided by the integration of all the entities connected to ADNs. The efficient integration of DERs into ADNs from an economic point-of-view will provide many benefits to end-users, among them, the possibility of increasing their flexibility, of reducing the electricity costs, of promoting RESs. Since existing energy market arrangements do not facilitate active coordination within distribution networks, new energy market mechanisms are emerging to allow the coordination in the distribution networks.

A local energy market is defined as "a platform on which prosumers and consumers trade energy supporting regional scopes such as a neighbourhood environment" (Zia et al. 2020) (Lezama et al. 2019). Following the classifications provided in Morstyn et al. (2020), the local energy markets can be classified into markets based on a centralised approach, a distributed approach, the unidirectional pricing and, finally, on peer-to-peer energy trading. While in a centralised approach the DERs are directly scheduled by a central operator (e.g., the DSO), in the distributed approach iterative negotiations and local decision making are adopted. A different approach is based on the determination of adequate prices based on day-ahead forecasts that will be sent as unidirectional price signals to prosumers. Finally, some recent proposals lay the foundation on the application of transactive energy concepts, such as peer-to-peer energy trading, to make possible the direct negotiation among prosumers and active end-users connected to a distribution network. In this respect, the GridWise Architecture Council (GridWise Architecture Council 2019) has broadly defined transactive energy as "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter".

Some insights with respect to the determination of prices in an ADN and concepts related to the transactive energy are provided in the next subsections.

1.7.1. Distribution Locational Marginal Prices

When designing an energy market in the new context of ADNs, it is crucial the choice of the pricing mechanism that should assure competition among the operators involved. Some authors have dedicated contributions to the extension of the concept of locational marginal prices from transmission level to distribution level by defining the so-called Distribution Locational Marginal Prices (DLMPs) (Li et al. 2014; Papavasiliou 2018; Bai et al. 2018; Yuan et al. 2019; Morstyn et al. 2020).

As highlighted by Papavasiliou (2018), price signals at the distribution level are needed to establish incentives for improving the efficiency of the generation, limiting losses in the distribution system, optimising the use of renewable sources, avoiding overloads or managing congestions; they are also essential for valuing ancillary services provided by distributed resources (e.g., responsive loads, generators and storage systems). Pricing energy and services at the distribution level is becoming an increasingly important aspect of electricity market design. The market design as well as the prices at distribution level have some peculiarities that do not belong to transmission markets; indeed, when a distribution system is considered, line losses, reactive power values and voltage levels have to be accounted for.

Li et al. (2014) proposes a method based on the computation of the DLMPs for a distribution network integrating aggregators of EVs. In particular, the objective of the proposed method is to relieve congestions due to the charging of the EVs. The EV aggregators are assumed to behave as price takers in the local market and an optimisation of the social welfare is performed to calculate the values of DLMPs. Bai et al. (2018) proposes a day-ahead market-clearing model for smart distribution systems including several types of DERs (i.e., DG, DS, MGs, and load aggregators). The DERs are supposed to be able to bid into the day-ahead distribution-level electricity market. When the day-ahead market is solved, the DLMPs for both active power and reactive power are determined. Since the model takes into consideration active power, reactive power, congestion, voltage levels and losses, the output of the day-ahead market will provide price signals for DERs to participate to the congestion management and voltage support.

A hierarchical mechanism is considered in Yuan et al. (2019) to evaluate the DLMPs. In particular, the considered levels are the transmission network, the distribution network, and, at the lowest level, the local embedded networks or MGs. A probabilistic computation of DLMPs has been recently proposed in Morstyn et al. (2020) with the application of the Point Estimate Method.

1.7.2. Transactive Energy for ADNs

Transactive Energy (TE) is a framework that can help the transformation of the distribution networks, which allows the effective integration of DERs and the active participation of the end-users in an ADN (Huang et al. 2019), (Rahimi et al. 2016). TE refers to direct energy exchanges among prosumers by extending competitive market mechanisms at the electricity wholesale level down to the retail level (Kok et al. 2016, Rahimi et al. 2016). These relatively new concepts aim at developing an open-access, distribution-level retail market where prosumers will have access to a competing market; another objective is a more economic and efficient management of the ADN operations. Local energy markets are organised in such a way DERs and end users will be able to participate in the market to trade the energy or ancillary services without affecting the grid functionality (Kumar Nunna & Srinivasan 2017).

In the TE framework, peer-to-peer (P2P) schemes, based on the concept of decentralised energy trading between peers, allows a better deployment of the DERs also using decentralised energy markets (Guerrero et al. 2020). Conceptually, these schemes allow the prosumers to directly share their electrical energy and investment. Such markets lay their foundation on a consumer-centric and bottom-up perspective and consumers will have the opportunity of buying energy (and services) as they prefer (Sousa et al. 2019).

The deployment of markets developed in the framework of TE need some emerging technologies, such as blockchain and other distributed ledger technologies (Guerrero et al. 2020; Zia et al. 2020). When the energy trading is involved, these technologies are needed for secure virtual transactions among users without intermediaries. Guerrero et al. (2020) and Siano et al. (2019) provide an overview on the enabling technologies for TE-based projects.

There are many proposals in the relevant literature and, also, some projects undergoing in the world. Many schemes and mechanisms have been proposed in the relevant literature to apply the TE concepts. Some of them are reviewed below.

A proposal for a TE market, for the optimal integration of DERs and MGs, is provided in Khorasany et al. (2020). A new market framework for DERs is required because value-based signals are needed. In the framework of the TE market, end-users and producers can exchange energy and other services in the distribution network under market rules. Khorasany et al. (2020) present and discuss the Monash MGs as a real-world implementation of a TE market with the detailed description of the layered enabling architecture that extends the physical MGs. The pricing mechanisms based on the proposed design is simulated.

The P2P energy trading platforms for distribution networks proposed in Morstyn et al. (2020) aims at setting a local energy market based on unidirectional locational pricing. To do that, a day-ahead locational pricing is proposed and solved in a probabilistic modelling in order to handle with demand uncertainty and upstream price uncertainty. The formulation of the problem includes network constraints and losses too. Local P2P energy trading platforms are integrated to additionally enable multi-period day-ahead P2P trading and single-period intra-day P2P trading, with transaction fees penalising energy transfers according to the probabilistic differential DLMPs.

Some proposals of TE markets rely on the MMG scenario; for instance in Kumar Nunna & Srinivasan (2017) every MG trades its energy with neighbouring MGs in the market and, in the frame of a TE framework, a comprehensive energy management system is set with the aim of managing auxiliary energy resources such as DR and DS for several smart MGs. Another proposal is provided in Liu et al. (2020) that considers a distributed day-ahead trading method for ADNs based on the technology of P2P; the method focuses on the congestion management in a MMG scenario.

Further insights and overviews can be found in Sousa et al. (2019), that provides a review of peer-to-peer electricity markets, giving also a perspective on the community-based markets (i.e., a community is formed by prosumers which collaborate), and in Zia et al. (2020), which is more focused on TE concepts applied to MGs.

1.8. Energy Management Aspects

1.8.1. Self-sufficiency and Self-consumption

In the recent decades, climate change has been raising concerns at the international level. In order to limit the global warming, the European Union has set climate and energy targets, which include the increase of the renewable energy share in the energy mix, the improvement of energy efficiency and the reduction of greenhouse gas emissions progressively up to 2050 (EUR-Lex 2020). Over the last years, energy policies led to the realisation and the cost reduction of technologies for renewable energy generation, for both large and small-scale use. As a result, businesses and households can produce electricity, fully or partially meeting their energy demand. Through the processes of Self-Consumption (SC) and Self-Sufficiency (SS), passive consumers are becoming active prosumers by totally or partially satisfying local consumption of energy by on-site production. The Self-Consumption $SC = E_{\text{lgc}}/E_{\text{gen}}$ is the ratio that quantify the on-site exploitation of the energy produced, calculated as the amount of electricity locally generated and consumed (E_{lgc}) with respect to the total local generation (E_{gen}) (Téllez Molina & Prodanovic 2013). The user independence of the grid is calculated by the Self-Sufficiency $SS = E_{\text{lgc}}/E_{\text{load}}$, as the ratio between the energy locally generated and consumed (E_{lgc}, the same numerator of the SC) with respect to the total consumption (E_{load}).

In order to clarify the difference between self-consumption and self-sufficiency, PV generation and load profiles of a monitored house in Northern Italy are used as an example in Figure 9. The time step is 5 min, in which the average values are considered.

The grid-connected PV plant with a rated power of 6 kW is used to supply the electric loads consisting of domestic appliances, induction cookers, and a heat pump for the production of domestic hot water. In this example, a cloudy summer day, the energy production from the PV system is 28.6 kWh. The total energy consumption is 14 kWh with power peaks at 1 a.m. and at 11 a.m. due to the heat pump, filling the storage tank of hot water, when its temperature is low. The green area is the PV electricity locally generated and consumed E_{lgc}=6.9 kWh, the green area identifies the surplus energy generated by the PV system and injected into the grid E_{surplus}=21.6 kWh, and the orange area indicates the energy absorbed from the grid E_{abs}=7.1 kWh. The total load E_{load}=14 kWh is the sum of E_{abs} and E_{lgc}. As a result, the self-sufficiency during this day is 50%, while the self-consumption is 24%. As a conclusion, during this day, the load is quite totally supplied by PV generation during light hours, with high surplus. The goal in future grids is to obtain both high SC and SS, i.e., the reduction of grid exchanges, both absorptions and injections. The consequences of high levels of SS and SC are several: higher acceptable capacity of renewable distributed generation into the electrical system, reduction of grid energy losses, mitigation of congestion problems and a less need for upgrading the electrical infrastructures (Senato della Repubblica 2018). The growing success of self-consumption is also related to the economic savings for energy users. Indeed, in some countries the renewable electricity has achieved *grid parity*, i.e., the expected unit cost of self-generated electricity is equal to or lower than the unit cost for electricity purchased from the grid.

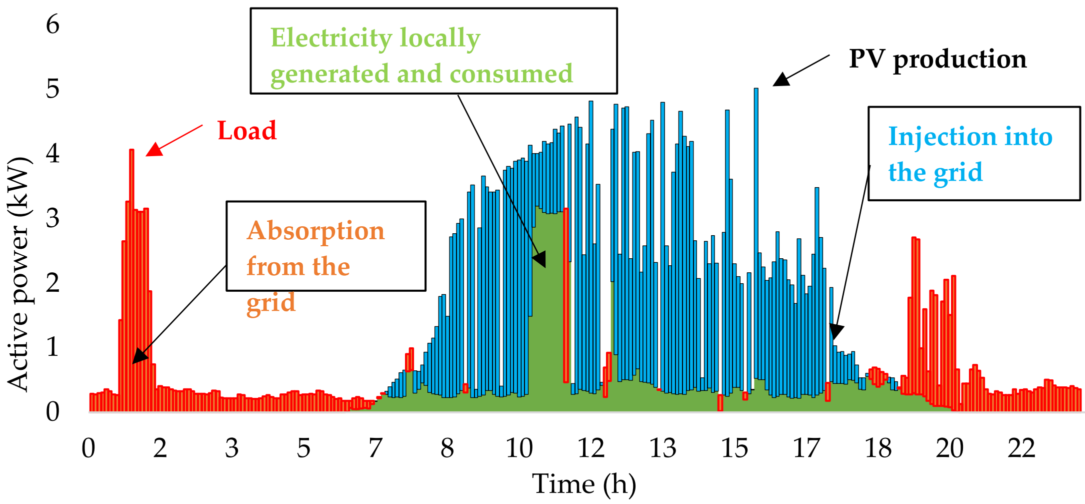

Figure 9. Measured PV generation and load profiles in a house in Northern Italy.

Several techniques are used in order to obtain high self-consumption and self-sufficiency rates. They can be maximised by storing the generated energy for a later use, acting on the consumption or production profiles. A short description of these concepts is presented in the next paragraphs.

1.8.2. Energy Storage Systems

In recent years, the number of studies regarding the combined use of energy storage systems and generation systems from RES has grown. The use of RES to produce electricity makes the role of storage systems strategic (Ould Amrouche et al. 2016). RES energy generation cannot be set to meet the users' needs, because it strictly depends on the availability of the resource. A proper charge and discharge logic stores energy when generation is high, in order to use it in low production hours. The action of storage systems reduces the amount of energy absorbed from the grid to satisfy users' demand, and high self-consumption can be achieved. Furthermore, since higher RES penetration threatens grid stability and power quality, the use of proper storage technologies mitigates these negative effects (Liang 2017).

There are several types of energy storage systems. They can be electrochemical, mechanical, electromagnetic or thermal storage. An overview of the energy storage technologies used in electric power systems can be found in Ould Amrouche et al. (2016) and Mahatkar & Bachawad (2017). Each technology has its own characteristics, such as lifetime, costs, energy density, charge/discharge times and efficiency. For example, batteries have a time of response within seconds and a limited power output, while pumped hydroelectric storage and compressed air energy storage have a time of response of minutes, can provide more power, but they require a geographical location with specific features. The choice of the right storage depends on the application (Mahatkar & Bachawad 2017, Zhou et al. 2015). The recent research is working on using storage from EVs to increase the self-sufficiency of the prosumers (Giordano et al. 2020).

1.8.3. Load Shifting

Load shifting is the temporal translation of the peak hours demand towards periods characterised by low demand. It attenuates the maximum and minimum of the daily energy consumption curve, and optimises the use of existing generation resources. Load shifting can be obtained through the adoption of policies that encourage the use of energy in certain time slots, such as specific tariff structures, or through the direct control of electrical appliances, the use of which is not tied to a specific moment of the day (Balakumar & Sathiya 2017).

In the case of self-generation of energy from intermittent RES, load shifting contributes to the increase in self-consumption, allowing the user to get an economic benefit and to better exploit the local energy resource. The economic savings obtained through the application of load shifting under time-varying energy pricing schemes are investigated in Farzambehboudi et al. (2018), Sinha & De (2016), and Vagropoulos et al. (2015). Moreover, load shifting and the other DR techniques help alleviating grid congestion problems, bringing benefits to the national grid (Liu et al. 2014).

1.8.4. Peak Demand Shaving

The generated power needs to match the demanded power at every time instant to avoid grid instability, voltage fluctuations and failures. For economic reasons, energy providers privilege the use of cheaper generating capacity, while more expensive power plants are turned on in case of peak demand conditions. The reduction of the peak load allows reducing the use of expensive generation capacity and increases providers' financial benefits. Thus, energy suppliers provide economic incentives for users to reduce peak loads (Benetti et al. 2016). For the case of self-generation of electricity, a better match between load and production profiles through peak demand shaving can enhance the exploitation of the local resource, increasing users' independence of the grid. In the literature, a large number of articles propose two methods for reducing load peaks: the use of energy storage systems and the application of DR techniques. Batteries are suggested for peak demand shaving for industrial customers (Oudalov et al. 2007; Bereczki et al. 2019), residential applications (Leadbetter & Swan 2012) and tertiary sector users (Telaretti & Dusonchet 2016). Dlamini & Cromieres (2012) and Shen et al. (2016) propose DR as management strategy of energy systems in order to provide peak load reduction.

1.8.5. Power Generation/injection Curtailment

In the literature there are several articles that show strategies for curtailing the energy generation from RES, especially wind energy (Liew & Strbac 2002; Mutale 2006; Siano et al.

2010). This limitation provides benefits for the electrical grid, avoiding overload and overvoltage events (Rossi et al. 2016). At the local level, power generation curtailment can contribute to match the energy production and consumption profiles in order to reduce the energy surplus. In PV generators, curtailments can be done by setting a limit to the inverter output, and the limitation is performed by moving away from the maximum power point in the current-voltage characteristic of the generator (Ahmad et al. 2015). In wind turbines, generation can also be reduced by changing the blades orientation of the turbines from the optimal one. These solutions are the simplest, but not the most efficient, because they do not take into account the energy balance with local loads and battery operation. In fact, a more advanced and expensive solution could be the continuous monitoring of the power injected in the grid, and the consequent limitation in the generation.

1.9. Grid Services

1.9.1. Ancillary Services

The term *Ancillary Services* (AS) is typically used in the international power systems community. It refers to *essential services* for the operation of the electrical system. In general, the ASs can be partitioned into:

- AS based on *capacity* (power): frequency control, load following, and reserves (with different response times).
- AS based on *energy*: energy balancing, loss compensation, other reserves.
- AS for *system management*: load balancing, services to improve the system dynamics, support to maintain system stability, congestion management, backup supply, and black-start capability.
- *Other* AS: voltage and reactive power support, data management services, metering and billing.

The inverters used for the grid interface of the generation from RES can potentially provide a number of additional services (Joos et al. 2000), such as reactive power compensation (better seen as *power conditioning* and waveform improvement in the presence of distorted waveforms and light flicker), voltage control (inside the capability curve limits), frequency control with addition of synthetic inertia (from some wind systems), and fault ride-through capability, due to the requirement of maintaining in operation the local generators as much as possible after a fault in the network.

In addition, AS may be provided by storage and EVs. Storage systems provide *load following* capabilities by smoothing the fluctuations due to the intermittent RES generation or to load variations. The storage charging and discharging has to be appropriately coordinated taking into account the time-dependent constraints on the storage capacity, ramping and autonomy. Efficiency and aging of the storage systems have to be considered as well. In the prospect of an increasing diffusion of the plug-in EVs, there is a potential for these vehicles to behave as moving storage. Moreover, if plug-in EVs are able to supply power at relatively fast rates, they can provide equivalent spinning reserves. The bi-directional energy flow in a plug-in EV is potentially useful also for providing balancing services.

1.9.2. Flexibility and Multi-energy Services

The *operational flexibility* has been defined in Ulbig & Andersson (2015), in a context with resources and reserves, as the technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power out-feed from the grid over time. More generally, the flexibility services can be seen in a wider way than ASs, because they involve also aspects not directly connected with the grid, such as direct load control at the demand side or interactions between different energy carriers in multi-energy systems (Chicco & Mancarella 2009).

However, also these interactions may have an indirect impact to provide flexibility at the grid connection point. Operational flexibility of ADNs has been addressed in Li et al. (2020) by flexibility availability and flexibility provision.

On the demand side, flexibility can be addressed for *individual* loads, by considering the availability of the users to postpone the operation of an appliance without reducing their comfort, or for the *aggregate* load, by considering possible benefits from the common management of a portfolio of users, as well as possible limitations due to the collective behaviour of the users in some periods of time (e.g., poor availability of the aggregate users for demand reduction in the morning period, Sajjad et al. 2016), and the aggregate flexibility that may be offered by loads controlled by thermostats (Hao et al. 2015; Zhao & Zhang 2017), or which offer flexibility services by using other types of control (Diaz Londono et al. 2020).

In more general terms, flexibility can be assessed in *energy community districts* by using a stochastic model for demand response resources (Good & Mancarella 2019). In this case, available flexibilities may come from *energy vector substitution*, enabled by the presence of an auxiliary gas boiler or a combined heat and power system, or electric heat pumps and storage (electrical or thermal), which provide wider room for flexible management of the energy mix. In addition, changes in the temperature inside the buildings and end-service curtailments can be exploited for increasing flexibility. In any case, flexibility has to be assessed by avoiding that the *thermal comfort* of the occupants is reduced below agreed or imposed limits.

References

Abu-Rub H, Holtz J, Rodriguez J, Baoming G (2010) Medium-voltage multilevel converters—State of the art, challenges, and requirements in industrial applications. IEEE T Ind Electron. 57:2581–2596.

Ahmad J, Spertino F, Ciocia A, Di Leo P (2015) A maximum power point tracker for module integrated PV systems under rapidly changing irradiance conditions. In: Abstracts of the 2015 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE). pp. 7–11.

Amin M (2004) Balancing market priorities with security issues. IEEE Power Energy M 2:30–38.

Aristidou P, Valverde G, Van Cutsem T (2015) Contribution of distribution network control to voltage stability: A case study. IEEE T Smart Grid 8:106–116.

Awerbuch S, Preston A (2012) The virtual utility: Accounting, technology & competitive aspects of the emerging industry. Springer Science & Business Media, Berlin.

Bahramara S, Mazza A, Chicco G, et al. (2020) Comprehensive review on the decision-making frameworks referring to the distribution network operation problem in the presence of distributed energy resources and microgrids. Int J Elec Power 115:105466.

Bai L, Wang J, Wang C, et al. (2017) Distribution locational marginal pricing (DLMP) for congestion management and voltage support. IEEE T Power Syst. 33:4061–4073.

Balakumar P, Sathiya S (2017) Demand side management in smart grid using load shifting technique. In: Abstracts of the 2017 IEEE International Conference on Electrical, Instrumentation and Communication Engineering (ICEICE), pp. 1–6.

Barker PP, De Mello RW (2000) Determining the impact of distributed generation on power systems. I. Radial distribution systems. In: 2000 IEEE Power Eng. Soc. Summer Meeting, pp. 1645–1656.

Benetti G, Caprino D, Della Vedova ML, Facchinetti T (2016) Electric load management approaches for peak load reduction: A systematic literature review and state of the art. Sustain. Cities Soc. 20:124–141.

Bereczki B, Hartmann B, Kertész S (2019) Industrial Application of Battery Energy Storage Systems: Peak shaving. In: Abstracts of the 7th International Youth Conference on Energy (IYCE), pp. 1–5.

Borghetti A, Bosetti M, Grillo S, et al. (2010) Short-term scheduling and control of active distribution systems with high penetration of renewable resources. IEEE Syst. J. 4:313–322.

Carpaneto E, Chicco G, Akilimali JS (2008) Loss partitioning and loss allocation in three-phase radial distribution systems with distributed generation. IEEE T Power Syst. 23:1039–1049.

Chicco G, Corona F, Porumb R, Spertino F (2014) Experimental indicators of current unbalance in building-integrated photovoltaic systems. IEEE J Photovolt. 4:924–934.

Chicco G, Mancarella P (2009) Distributed multi-generation: A comprehensive view. Renew Sust Energ Rev 13:535–551.

Chicco G, Mazza A (2019) New insights for setting up contractual options for demand side flexibility. Journal of Engineering Sciences and Innovation 4:381–398.
Chicco G, Mazza A (2020) Understanding the Value of Net Metering Outcomes for Different Averaging Time Steps. In: Abstracts of the 2020 International Conference on Smart Energy Systems and Technologies (SEST), pp 1–6.
CIGRÉ (2009) WG 6.11 - Active Distribution Networks: general features, present status of implementation and operation practices.
CIGRÉ (2014) WG C6.19 - Planning and Optimization Methods for Active Distribution Systems.
CIGRÉ (2015) WG C6.22 - Microgrids 1 Engineering, Economics, & Experience.
Ciocia A, Boicea VA, Chicco G, et al. (2018) Voltage control in low-voltage grids using distributed photovoltaic converters and centralized devices. IEEE T Ind. Appl. 55:225–237.
Diaz-Londono C, Enescu D, Ruiz F, Mazza A (2020) Experimental modeling and aggregation strategy for thermoelectric refrigeration units as flexible loads. Applied Energy 272:115065.
Dlamini NG, Cromieres F (2012) Implementing peak load reduction algorithms for household electrical appliances. Energy Policy 44:280–290.
Doudna JH (2001) Overview of California ISO summer 2000 demand response programs. In: Abstracts of the 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 01CH37194). pp 228–233.
Ehsan A, Yang Q (2019) State-of-the-art techniques for modelling of uncertainties in active distribution network planning: A review. Applied Energy 239:1509–1523.
ENTSO-E (2013) European network of transmission system operators for electricity: Supporting Document for the Network Code on Load-Frequency Control and Reserves.
Eriksson R, Modig N, Elkington K (2017) Synthetic inertia versus fast frequency response: a definition. IET Renewable Power Generation 12:507–514.
EUR-Lex: Access to European Union law. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52018DC0773. Accessed 30 Oct 2020.
European Commission (2006) European SmartGrids Technology Platform: Vision and Strategy for Europe's Electricity Networks of the Future. http://ec.europa.eu/research/energy/pdf/smartgrids_en.pdf . Accessed 2 Nov 2020.
European Commission (2015) Delivering a New Deal for Energy Consumer. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015DC0339. Accessed 2 Nov 2020.
European Commission (2016) Clean Energy for all Europeans Package. https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en. Accessed 2 Nov 2020.
Farzambehboudi Y, Erdinç O, Rifat Boynueğri A, Ucun L, Öz MA (2018) Economic Impact Analysis of Load Shifting in a Smart Household. In: Proceedings of 2018 International Conference on Smart Energy Systems and Technologies (SEST), Sevilla, Spain, 10–12 September 2018.
Giordano F, Ciocia A, Di Leo P, Mazza A, Spertino F, Tenconi A, Vaschetto S (2020) Vehicle-to-Home Usage Scenarios for Self-Consumption Improvement of a Residential Prosumer With Photovoltaic Roof. IEEE T Ind. Appl. 56(3):2945–2956.
Giovanelli C, Kilkki O, Sierla S, Seilonen I, Vyatkin V (2018) Task allocation algorithm for energy resources providing frequency containment reserves. IEEE T Ind. Inform. 15(2): 677–688.
Good N, Mancarella P (2019) Flexibility in multi-energy communities with electrical and thermal storage: A stochastic, robust approach for multi-service demand response. IEEE T Smart Grid 10(1):503–513.
Guerrero J, Gebbran D, Mhanna S, Chapman AC, Verbič G (2020) Towards a transactive energy system for integration of distributed energy resources: Home energy management, distributed optimal power flow, and peer-to-peer energy trading, Renew Sust Energ Rev 132:110000.
GridWise Architecture Council (2019) GridWise Transactive Energy Framework, Version 1.1. https://www.gridwiseac.org/. Accessed 21 October 2020.
Hao H, Sanandaji BM, Poolla K, Vincent TL (2015) Aggregate Flexibility of Thermostatically Controlled Loads. IEEE T Power Syst. 30(1):189–198.
Horne J, Flynn, D, Littler T (2004) Frequency stability issues for islanded power systems. In: Proceedings of IEEE PES Power Systems Conference and Exposition, New York, USA, 10–13 October 2004.
Huang Q, McDermott TE, Tang Y, Makhmalbaf A, Hammerstrom DJ, Fisher AR, Marinovici LD, Hardy T (2019) Simulation-Based Valuation of Transactive Energy Systems. IEEE T Power Syst. 34(5):4138–4147.
Huber JE, Kolar JW (2019) Applicability of Solid-State Transformers in Today's and Future Distribution Grids. IEEE T Smart Grid 10(1):317–326.

Hussain A, Bui V-H, Kim H-M (2016) Robust optimization-based scheduling of multimicrogrids considering uncertainties. Energies 9(4):278.
IEEE (2000) The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition. IEEE Std 100-2000.
IEEE Power and Energy Society (2017) IEEE Standard for the Specification of Microgrid Controllers. In: IEEE Std. 2030.7. The Institute of Electrical and Electronics Engineers, Piscataway, NJ, USA, pp 1–43.
Jenkins N, Enanayake JB, Strbac G (2003) Distributed generation, IET.
Ji S, Zhang Z, Wang F (2017) Overview of High Voltage SiC Power Semiconductor Devices: Development and Application. CES Trans on Electr Mach and Syst 1(3):254–264.
Joos G, Ooi BT, McGillis D, Galiana FD, Marceau R (2000) The potential of distributed generation to provide ancillary services. In: Proceedings of IEEE Power Engineering Society Summer Meeting, Seattle, WA, USA, 16–20 July 2000.
Kanechika M, Uesugi T, Kachi T (2010) Advanced SiC and GaN power electronics for automotive systems. In: Proceedings of 2010 International Electron Devices Meeting, San Francisco, CA, 6–8 December 2010. doi: 10.1109/IEDM.2010.5703356.
Khorasany M, Azuatalam D, Glasgow R, Liebman A, Razzaghi R (2020) Transactive Energy Market for Energy Management in Microgrids: The Monash Microgrid Case Study. Energies 13(8):2010.
Kok K, Widergren S (2016) A society of devices: Integrating intelligent distributed resources with transactive energy. IEEE Power Energy Mag 14(3):34–45.
Kasaei MJ, Gandomkar M, Nikoukar J (2017) Optimal management of renewable energy sources by virtual power plant. Renew Energy 114:1180–1188.
Kersting WH (2002) Distribution System Modeling and Analysis. CRC Press, Boca Raton.
Kumar D, Zare F, Ghosh A (2017) DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects. IEEE Access 5:12230–12256.
Kumar Nunna HSVS, Srinivasan D (2017) Multiagent-based transactive energy framework for distribution systems with smart microgrids, IEEE T Ind. Inform. 13(5):2241–2250.
Kundur P, Paserba J, Ajjarapu V, Andersson G, Bose A, Canizares C, Hatziargyriou N, Hill D, Stankovic A, Taylor C, Van Cutsem T (2004) Definition and classification of power system stability IEEE/CIGRE Joint Task Force on stability terms and definitions. IEEE T Power Syst. 19(3):1387–1401.
Lakervi E, Holmes EJ (2007) Electricity distribution network design (2nd ed.). Institution of Engineering and Technology, UK.
Lasseter R (2001) Role of distributed generation in reinforcing the critical electric power infrastructure. In: Proceedings of 2001 IEEE Power Engineering Society Winter Meeting, Columbus, OH, 28 January–1 February 2001.
Lasseter R, Akhil A, Marnay C, Stevens J, Dagle J, Guttromson R, Sakis Meliopoulous A. Yinger R, Eto J (2002) White paper on integration of distributed energy resources. The CERTS microgrid concept. LBNL-50829.
Leadbetter J, Swan L (2012) Battery storage system for residential electricity peak demand shaving. Energy Build 55:685–692.
Lezama F, Soares J, Hernandez-Leal P, Kaisers M, Pinto T, Vale Z (2019) Local Energy Markets: Paving the Path Toward Fully Transactive Energy Systems. IEEE T Power Syst. 34(5):4081–4088.
Li R, Wu Q, Oren SS (2014) Distribution Locational Marginal Pricing for Optimal Electric Vehicle Charging Management. IEEE T Power Syst. 29(1):203–211.
Li P, Wang Y, Ji H, Zhao J, Song G, Wu J, Wang C (2020) Operational flexibility of active distribution networks: Definition, quantified calculation and application. Int J of Electr Power & Energy Syst 119:105872.
Liang X (2017) Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources. IEEE T Ind. Appl. 53(2):855–866.
Liew SN, Strbac G (2002) Maximising penetration of wind generation in existing distribution networks. IEE Proc Gener Transm Distrib 149(3):256–262.
Lips HP (1998) Technology trends for HVDC thyristor valves. In: Proceedings of 1998 International Conference on Power System Technology (POWERCON '98), Beijing, China, 18–21 August 1998
Liu W, Wu Q, Wen F, Østergaard J (2014) Day-Ahead Congestion Management in Distribution Systems Through Household Demand Response and Distribution Congestion Prices. IEEE T Smart Grid 5(6):2739–2747.
Liu H, Li J, Ge S, He X, Li F, Gu C (2020) Distributed Day-Ahead Peer-to-Peer Trading for Multi-Microgrid Systems in Active Distribution Networks. IEEE Access 8:66961–66976.

Ludois D, Venkataramanan G (2010) An Examination of AC/HVDC Power Circuits for Interconnecting Bulk Wind Generation with the Electric Grid. Energies 3:1263–1289.
Mahatkar TK, Bachawad MR (2017) An Overview of Energy Storage Devices for Distribution Network. In: Proceedings of 2017 International Conference on Computation of Power, Energy Information and Communication (ICCPEIC), Melmaruvathur, India, 22–23 March 2017.
Majumder R (2013) Aspect of voltage stability and reactive power support in active distribution. IET Gener Transm Distrib 8(3):442–450.
Mandrile F, Musumeci S, Carpaneto E, Bojoi R, Dragičević T, Blaabjerg F (2020) State-Space Modeling Techniques of Emerging Grid-Connected Converters. Energies 13:4824.
Martin-Martínez F, Sánchez-Miralles A, Rivier M (2016) A literature review of Microgrids: A functional layer based classification. Renew Sust Energ Rev 62:1133–1153.
Martini L, Radaelli L, Brunner H, Caerts C, Morch A, Hanninen S, Tornelli C (2015) ELECTRA IRP approach to voltage and frequency control for future power systems with high DER penetration. In: Proceedings of 23rd International Conference on Electricity Distribution (CIRED 2015), Lyon, France, 15–18 June 2015.
Martins VF, Borges CLT (2011) Active Distribution Network Integrated Planning Incorporating Distributed Generation and Load Response Uncertainties. IEEE T Power Syst. 26(4): 2164–2172.
Mazza A, Carpaneto E, Chicco G, Ciocia A (2018) Creation of Network Case Studies with High Penetration of Distributed Energy Resources. In: Proceedings of UPEC 2018, Glasgow, UK, 4–7 September 2018.
Mazza A, Chicco G (2019) Losses Allocated to the Nodes of a Radial Distribution System with Distributed Energy Resources – A Simple and Effective Indicator. In: Proceedings of 2nd International Conference on Smart Energy Systems and Technologies (SEST 2019), Porto, Portugal, 9–11 September 2019.
Morstyn T, Teytelboym A, Hepburn C, McCulloch MD (2020) Integrating P2P Energy Trading With Probabilistic Distribution Locational Marginal Pricing. IEEE T Smart Grid 11(4):3095–3106.
Muhanji SO, Muzhikyan A, Farid AM (2018) Distributed Control for Distributed Energy Resources: Long-Term Challenges and Lessons Learned. IEEE Access 6:32737–32753.
Musumeci S (2015) Gate charge control of high-voltage Silicon-Carbide (SiC) MOSFET in power converter applications. In: Proceedings of 2015 International Conference on Clean Electrical Power (ICCEP), Taormina, Italy, 16–18 June 2015. doi: 10.1109/ICCEP.2015.7177569.
Mutale, J (2006) Benefits of Active Management of Distribution Networks with Distributed Generation. In: Proceeding of 2006 IEEE PES Power Systems Conference and Exposition, Atlanta, Georgia, USA, 29 October – 1 November 2006.
Nan S, Zhou M, Li G (2018). Optimal residential community demand response scheduling in smart grid. Applied Energy 210:1280–1289.
Nosratabadi SM, Hooshmand RA, Gholipour E (2017) A comprehensive review on microgrid and virtual power plant concepts employed for distributed energy resources scheduling in power systems. Renew Sust Energ Rev 67:341–363.
Ochoa LF, Padilha-Feltrin A, Harrison GP (2006) Evaluating distributed generation impacts with a multiobjective index. IEEE T Power Deliv. 21(3):1452–1458.
Oudalov A, Cherkaoui R, Beguin A (2007) Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application. In: Proceedings of 2007 IEEE Lausanne Power Tech, Lausanne, Switzerland, 1–5 July 2007.
Ould Amrouche S, Rekioua D, Rekioua T, Bacha S (2016) Overview of energy storage in renewable energy systems. Int. J. of Hydrogen Energy 41(45):20914–20927.
Papavasiliou A (2018) Analysis of Distribution Locational Marginal Prices. IEEE T Smart Grid 9(5): 4872–4882.
Parhizi S, Lotfi H, Khodaei A, Bahramirad S (2015) State of the art in research on microgrids: A review. IEEE Access 3:890–925.
Paterakis NG, Mazza A, Santos SF, Erdinç O, Chicco G, Bakirtzis AG, Catalão JPS (2015) Multi-objective reconfiguration of radial distribution systems using reliability indices. IEEE T Power Syst. 31(2):1048–1062.
Pau M, Patti E, Barbierato L, Estebsari A, Pons E, Ponci F, Monti A (2018) A cloud-based smart metering infrastructure for distribution grid services and automation. Sustainable Energy, Grids and Networks 15:14–25.
Ponocko J, Milanovic JV (2019) The Effect of Load-follow-generation Motivated DSM Programme on Losses and Loadability of a Distribution Network with Renewable Generation. In: Proceedings of 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), Bangkok, Thailand, 19–23 March 2019.

Pudjianto D, Ramsay C, Strbac G (2007) Virtual power plant and system integration of distributed energy resources. IET Renew Power Gener 1(1):10–16.
Rahimi F, Ipakchi A, Fletcher F (2016) The changing electrical landscape: end-to-end power system operation under the transactive energy paradigm. IEEE Power Energy Mag 14(3):52–62.
Rodriguez J et al (2009) Multilevel Converters: An Enabling Technology for High-Power Applications. Proc of the IEEE 97(11):1786–1817. doi: 10.1109/JPROC.2009.2030235.
Rossi M, Viganò G, Moneta D, Clerici D, Carlini C (2016) Analysis of active power curtailment strategies for renewable distributed generation. In: Proceeding of 2016 AEIT International Annual Conference (AEIT), Capri, Italy, 5–7 October 2016.
Sajjad IA, Chicco G, Napoli R (2016) Definitions of Demand Flexibility for Aggregate Residential Loads. IEEE T Smart Grid 7(6):2633–2643.
Schettler F, Balavoine M, Callavik M, Corbett J, Kuljaca N, Larsen V, MacLeod N, Sonerud B (2012) Roadmap to the supergrid technologies. Friends of the SuperGrid.
Senato della Repubblica (2018) RSE – Ricerca sul Sistema Energetico: natura, missione, attività. http://www.senato.it/application/xmanager/projects/leg18/attachments/documento_evento_procedura_commissione/files/000/000/945/2018_12_21_-_RSE.pdf. Accessed 30 Oct 2020.
Shen J, Jiang C, Liu Y, Qian J (2016) A Microgrid Energy Management System with Demand Response for Providing Grid Peak Shaving. Electr Power Compon Syst 44(8):843–852.
Siano P, Chen P, Chen Z, Piccolo A (2010) Evaluating maximum wind energy exploitation in active distribution networks. IET Gener Transm Distrib 4(5):598–608.
Siano P, De Marco G, Rolán A, Loia V (2019) A Survey and Evaluation of the Potentials of Distributed Ledger Technology for Peer-to-Peer Transactive Energy Exchanges in Local Energy Markets. IEEE Syst J 13(3):3454–3466.
Simonov M (2014) Hybrid scheme of electricity metering in Smart Grid. IEEE Syst J 8(2): 422–429.
Simonov M, Chicco G, Zanetto G (2017) Event-Driven Energy Metering: Principles and Applications. IEEE T Ind Appl 53(4):3217–3227.
Simmonds G (2002) Regulation of the UK electricity industry: University of Bath School of Management.
Smart Grid Coordination Group (2012) Smart Grid Reference Architecture. CEN-CENELEC-ETSI, Tech. Rep.https://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf. Accessed 2 Nov 2020.
Smart Energy Demand Coalition (2016) Explicit and Implicit Demand-Side Flexibility, Position paper September 2016.
Sinha A, De M (2016) Load shifting technique for reduction of peak generation capacity requirement in smart grid. In: Proceeding of 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), Delhi, India, 4–6 July 2016.
Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E (2019) Peer-to-peer and community-based markets: A comprehensive review, Renew Sust Energ Rev 104:367–378.
Spertino F, Di Leo P, Corona F, Papandrea F (2012) Inverters for grid connection of photovoltaic systems and power quality: Case studies. In: Proceedings of 2012 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Aalborg, Denmark, 25–28 June 2012.
Spertino F, Ahmad J, Ciocia A, Di Leo P, Giordano F (2017a) Maximization of self-sufficiency with grid constraints: PV generators, wind turbines and storage to feed tertiary sector users. In: Proceedings of 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Washington, DC, USA, 25–30 June 2017.
Spertino F, Ahmad J., Ciocia A, Di Leo P (2017b) How much is the advisable self-sufficiency of aggregated prosumers with photovoltaic-wind power and storage to avoid grid upgrades?. In: Proceedings of 2017 IEEE Industry Applications Society Annual Meeting, Cincinnati, OH, USA, 1–5 October 2017.
Telaretti E, Dusonchet L (2016) Battery storage systems for peak load shaving applications: Part 1: Operating strategy and modification of the power diagram. In: Proceedings of 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), Florence, Italy, 7–10 June 2016.
Téllez Molina MB, Prodanovic M (2013) Profitability assessment for self-sufficiency improvement in grid-connected non-residential buildings with on-site PV installations. In: Proceedings of 2013 International Conference on Clean Electrical Power (ICCEP), Alghero, Italy, 11–13 June 2013.
Terna (2008) Italian Grid Code, Annex A15: Partecipazione alla Regolazione di Frequenza e Frequenza-Potenza, Technical Report, July 2008.

Thomson AW, Perez Y (2020) Vehicle-to-Everything (V2X) energy services, value streams, and regulatory policy implications. Energy Policy 137:111136.

Tindemans SH, Trovato V, Strbac G (2015) Decentralized Control of Thermostatic Loads for Flexible Demand Response. IEEE T Contr. Syst. T 23(5):1685–1700.

UCTE (2004) Appendix 1: Load-frequency control and performance, Technical Report, June 2004.

U.S. (2007) Energy Independence and Security Act of 2007, The Senate and House of Representatives of the United States of America, Public Law 110–140—Dec. 19, 2007. Accessed 2 Nov 2020 https://www.gpo.gov/fdsys/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf. Accessed 2 Nov 2020.

Ulbig A, Andersson G (2015) Analyzing operational flexibility of electric power systems. Electr Power & Energy Syst 72:155–164.

Vagropoulos SI, Katsolas ID, Bakirtzis AG (2015) Assessment of load shifting potential on large insular power systems. In: Proceedings of 2015 IEEE Eindhoven PowerTech, Eindhoven, Netherlands, 29 June – 2 July 2015.

Vobecký J et al (2017) Silicon Thyristors for Ultrahigh Power (GW) Applications. IEEE T Electron Dev. 64(3):760–768.

Vu K, Begovic MM, Novosel D (1997) Grids get smart protection and control. IEEE Comput. Appl. Pow. 10(4):40–44.

Wang H, Ma K (2016) IGBT technology for future high-power VSC-HVDC applications. In: Proceedings of 12th IET International Conference on AC and DC Power Transmission (ACDC 2016), Beijing, China, 28–29 May 2016.

Wang L et al (2017) A Three-Level T-Type Indirect Matrix Converter Based on the Third-Harmonic Injection Technique. IEEE Journal of Emerging and Selected Topics in Power Electronics 5(2):841–853.

Weedy BM, Cory BJ, Jenkins N, Ekanayake JB, Strbac G (2012) Electric Power Systems, Chapter 4, Control of Power and Frequency, J. Wiley and Sons, 5th Edition.

Xu Z, Zeng Z, Peng J, Zhang Y, Zheng C, Yang P (2018) Analysis on the organization and Development of multi-microgrids. Renew Sust Energ Rev 81: 2204–2216.

Yu S, Fang F, Liu Y, Liu J (2019) Uncertainties of virtual power plant: Problems and countermeasures. Applied Energy 239:454–470.

Yuan Z, Hesamzadeh MR, Biggar DR (2019) Distribution Locational Marginal Pricing by Convexified ACOPF and Hierarchical Dispatch. IEEE T Smart Grid 9(4):3133–3142.

Zeng Z, Yang H, Zhao R, Cheng C (2013) Topologies and control strategies of multifunctional grid-connected inverters for power quality enhancement: a comprehensive review. Renew Sust Energ Rev 24:223–270.

Zhang J, Xu S, Din Z, Hu X (2019) Hybrid Multilevel Converters: Topologies, Evolutions and Verifications. Energies 12:615.

Zhao L, Zhang W (2017) A geometric approach to aggregate flexibility modeling of thermostatically controlled loads. IEEE T Power Syst. 32(6):4721–4731.

Zhou X, Lin Y, Ma Y (2015) The overview of energy storage technology. In: Proceedings of 2015 IEEE International Conference on Mechatronics and Automation (ICMA), Beijing, China, 2–5 August 2015.

Zia MF, Benbouzid M, Elbouchikhi E, Muyeen SM, Techato K, Guerrero JM (2020) Microgrid transactive energy: review, architectures, distributed ledger technologies, and market analysis. IEEE Access 8:19410 –19432.