Review

Multidisciplinary Approach for the Development of Smart Distribution Networks

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Abstract: Electric power systems are experiencing relevant changes involving the growing penetration of distributed generation and energy storage systems, the introduction of electric vehicles, the management of responsive loads, the proposals for new energy markets and so on. Such evolution is pushing for a paradigm shift: the management must move from traditional planning and manual intervention to full "smartization" of medium and low voltage networks. Peculiarities and criticalities of future power distribution networks originate from the complexity of the system that includes both the physical aspects of electric networks and the cyber aspects, like data elaboration, feature extraction, communication, supervision and control; only fully integrated advanced monitoring systems can foster this transition towards network automation. The design and development of such future networks require distinct kinds of expertise in the industrial and information engineering fields. In this context, this paper provides a comprehensive review of current challenges and multidisciplinary interactions in the development of smart distribution networks.

1. Introduction

The need for lowering the dependence of power systems on fossil fuels has led many government agencies to define strict constraints on electricity production from renewable energy sources (RES); for example, the European Union sets that RES contribution to overall energy consumption should be at least 20% by 2020; this share is also expected to reach at least 55% in 2050 [1,2]. Consequently, a massive and rapid growth of RES has been experienced in the last decade, especially with reference to the installation of several small-medium size wind and photovoltaic power plants connected to power distribution networks (DNs). Referring to the last five years, RES investments have been at least $ 200 billion per year, particularly $ 265 billion in 2016 [3]. These huge investments led to an overall share of the global energy consumption supplied by RES of about 19% in 2015 and an overall share of electricity production coming from RES of about 25% in 2016 [3]; some studies also foresee that the share of global energy consumption coming from RES will achieve about 80% in 2050 [3,4]. Such a huge distributed generation (DG), however, is affected by poor programmability and significant power fluctuations caused by high sensitivity to environmental conditions. Consequently, given the growing global electricity consumption and the increasing use of electric vehicles (EVs), the traditional centralized structure of the electrical power system is no longer suitable and even technically unsustainable.

In this scenario, distributed energy resources (DERs) cover a fundamental role for enabling smart power systems; DERs consist of a combination of energy storage systems (ESSs), RES and

conventional power plants, which act as local generation sources in DNs [5,6]. Consumers/prosumers with multiple DERs and/or ESSs in the DN will be coordinated to form integrated energy systems, such as microgrids (MGs), virtual power plants (VPP), energy hubs (EHs) or multi-energy systems (MESs), in order to achieve appropriate and efficient operation and management. Particularly, conventional power plants and ESSs are intended to compensate for poor programmability and intermittency of RES in order to ensure proper electricity supply. In this context, the employment of suitable energy management systems (EMSs) is of paramount importance for integrating DERs into DNs, namely for enabling smart grid (SG) paradigm [5,7,8]. These concepts seem unavoidable for achieving a sustainable electricity infrastructure, i.e. power systems able to monitor, manage and possibly optimize production, transport, distribution and consumption of electricity in accordance with specific features and operating constraints of all their components.

Focusing on the DN infrastructure upgrade roadmap, it reveals that DNs are deeply evolving [9]**Error! Reference source not found.**: the passive management applied by distribution network operator is changing towards the more active role of distribution system operator (DSO). The DSO will act to satisfy active and reactive power needs and will have to maintain acceptable voltage levels and avoid congestions, which may arise, e.g. due to DG; the DSO will be potentially devoted to the management of new kind of energy and ancillary service markets among the distribution players or between the DSO and the transmission system operator [10]. These activities must rely on an accurate knowledge of the operating conditions provided by the monitoring system (MS) and on an efficient and secure communication infrastructure. New communication systems (CSs) and their interfacing with the power system elements will be necessary, as well as the development of monitoring and management systems able to operate in a smart way the energy production, consumption and storage within the DN [11].

The reason for this paper is thus the necessity to reconsider the evolution of DN and the different ongoing steps from a unified and multidisciplinary perspective. The aim is to give a review of the efforts and challenges of different disciplines all together in the smart distribution network (SDN) context, so that the multidisciplinary solutions are highlighted and mutual relationships can emerge. The paper is organized as follows. In Section 2 the requirements of multidisciplinary efforts for enabling SDN paradigm are underlined. In Section 3 the open challenges concerning the monitoring of SDNs are presented. In Section 4 the aspects related to the management and control of DERs within SDN frameworks are examined. Section 5 focuses on communication and data security in SDN. Concluding remarks are reported in Section 6.

2. Key interactions in design, development and operation of smart distribution networks

2.1. The transition from passive towards smart distribution networks

The massive penetration of DERs has been leading towards a new approach in DN design, development and operation. Until now, DN has been regarded as a passive termination of the transmission network, having the goal of supplying reliably and efficiently the end users. According to this scheme, DNs are radial, with unidirectional power flows and with a simple and efficient protection scheme. A greater penetration of DERs is changing disruptively this well consolidated environment: definitely, DNs will be no longer passive and a gradual, but ineluctable, transformation towards a new kind of active networks has been foreseen.

In this regard, bidirectional power flow patterns may require changes in the network control and protection strategies, enhanced distribution automation, enforcement of DN infrastructure and/or greater degrees of information management and control according to the SG paradigm. With RES, such as photovoltaic and wind power plants, which will continue in the coming years to introduce critical issues in the short-term DN planning and operation, the transition towards this new status will require:

- novel DN structures, such as MG, VPP and EH, as well as new frameworks for energy management and electricity market scenarios;

- advanced, accurate and reliable monitoring systems, able to observe and estimate DN status at greater resolution in space and time, in order to support DN control and management;
- appropriate management and control systems, able to optimize DN bidirectional power flows, energy saving and economic benefits according to the SG paradigm;
- communication and data processing systems, which have to guarantee seamless interactions among all DN components and proper level of cyber-security.

In this scenario, SDN will be implemented following the SG paradigm, namely SDN will intelligently integrate the actions of all actors connected to it, such as generators, suppliers, aggregators and consumers, in order to efficiently deliver sustainable, economical and secure electricity supplies. To achieve these goals, a vast integration of sensors and measurement devices for collecting data across the grid is also needed. In addition, SDN will exploit information and communication technologies on top of the electric network to improve the reliability, security, and efficiency (both economic and energetic) of the overall electric system. Based on such measurement and communication systems, SDN will be able to integrate DERs at any point of the network, especially at the consumer/prosumer level (equipped with individual EMS). Thus, this SDN structure creates the opportunity for any consumer/prosumer on the grid to become an energy/power supplier and take part in energy trading mechanism; this is the key for consumer to be converted into an active energy citizen.

Researches on empowering these energy citizens are carrying out by introducing the ideas of smart buildings, smart energy communities, smart cities, etc., in order to achieve the decarbonization target. EU commission, for instance, is strongly focusing on these aspects since it proposes new rules for consumer-centered clean energy transition, where consumers are active and central players on the energy market of the future. Consumers/prosumers will have a better choice of their energy retailer and the possibility to produce and sell their own electricity with real-time response to price signals. Hence, for a better operation and management, consumers/prosumers with multiple DERs can be coordinated to form an integrated energy system, such as MG, VPP and EH. Local consumers/prosumers and communities can be engaged with these with the aim to empower energy citizens or uplift smart energy communities.

2.2. Main schemes and components of smart distribution networks

Innovative SDN schemes and operation policies can be proposed to help facing the new challenges, based on the exploitation of communication and information technologies to increase the observability and controllability of DERs, among which MGs. In particular, the power infrastructure might benefit of multiple MGs, which can be referred as networked microgrids [12] or multi-microgrids (MMGs) [13], by using their typical features for reliability and resiliency with a new operational strategy able to exploit MMG normal operation and self-healing to support and exchange electricity with various actors in the power infrastructure. MMGs are connected to the main power distribution backbone with a designed communication network. In each MG, the EMS schedules the operation, while all EMSs are globally optimized. In the normal operation mode, the objective is to schedule dispatchable DG, ESS, and controllable loads to minimize the operating costs and maximize the supply adequacy of each MG. When a generation deficiency or fault happens in a MG, the architecture can switch to the self-healing mode and the local generation capacities of other MGs can be used to enhance the SDN resilience [12,14].

According to this view, a possible evolution of existing DNs is depicted in Figure 1. The SDN will consist of an interconnected medium voltage (MV) and low voltage (LV) networks with mixed communication infrastructure between the distribution/energy management system (DMS/EMS) of the network, communicating with the supervisory, control and data acquisition (SCADA) system and the active resources in the network by means of Intelligent Electronic Devices (IEDs), as schematized in Figure 1. In the SDN, a centralized/decentralized DMS/EMS supervises the operation by gathering measurements of the main electric variables from IEDs and, according to the control scheme, modifies the set point of DERs directly connected to MV network and interacts with the energy management of LV DERs and/or local MG controllers. The reorganization of the DN into MMGs can determine

significant benefits to the customers, with the opportunity of reducing the energy bill and increasing the perceived reliability, to the DSO, that may postpone or avoid investments or activate new business, and to the environment, thanks to the exploitation of RES. All these goals can be achieved by the use of advanced management and control that necessarily rely on advanced monitoring and communication technologies. The SG paradigm will also allow users to actively contribute to the optimization of the overall electrical system and will require a multidisciplinary approach to be designed and set up.
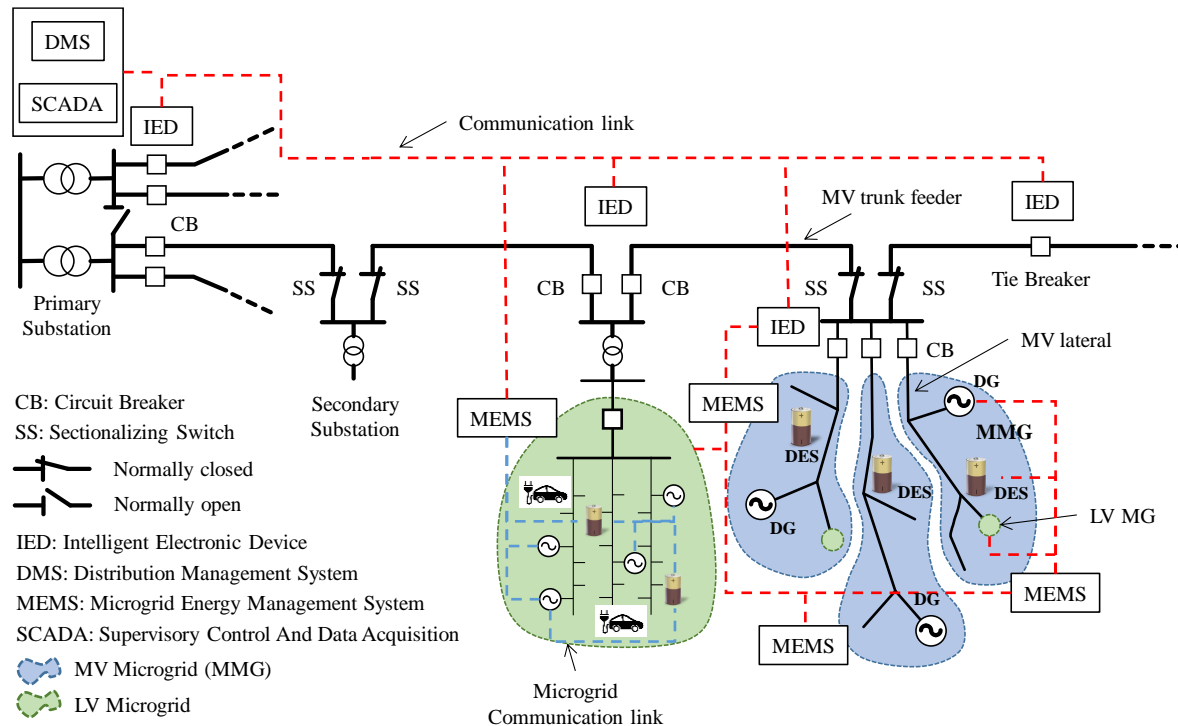
Figure 1. A feasible scheme of a smart distribution network.

There are several pilot projects and examples all over the world that have been set up in order to prove both technical and economic feasibility of both SG and MG [15], whose main aim is a more efficient and reliable electricity supply, appropriately coordinated with the electricity market and local consumption, without the need to renew the supporting structure of the pre-existing power system significantly. Particularly, MGs can bring several advantages to DNs, among which local voltage and/or frequency regulations, line losses minimization and a better matching between production and consumption profiles. Considering the power system as a whole, MGs can also determine significant energy saving, increased reliability and reduced greenhouse gases emissions.

A different approach that permits implementing SG functions without strictly owning/controlling the power network is VPP (Figure 2); this may be considered as a form of "Internet of Energy", able to integrate different small energy sources, such as nanogrids, EVs, DG and ESSs. The various DERs do not need to be physically interconnected and can be remotely controlled by means of Information and Communication Technology (ICT) and EMS. A recognized potential of VPP is the possibility of implementing innovative energy market scenarios [16]. VPP can deliver the energy demanded at peak usage times by fulfilling a request from a DSO/aggregator; it can also store any surplus energy, giving to the energy aggregator more options, for instance by balancing the intermittency and variability of RES [17]. The VPP obtained by clustering DERs will be able to monitor and control the power absorbed by electrical users and provide dispatching/flexibility services to the electricity distributor.
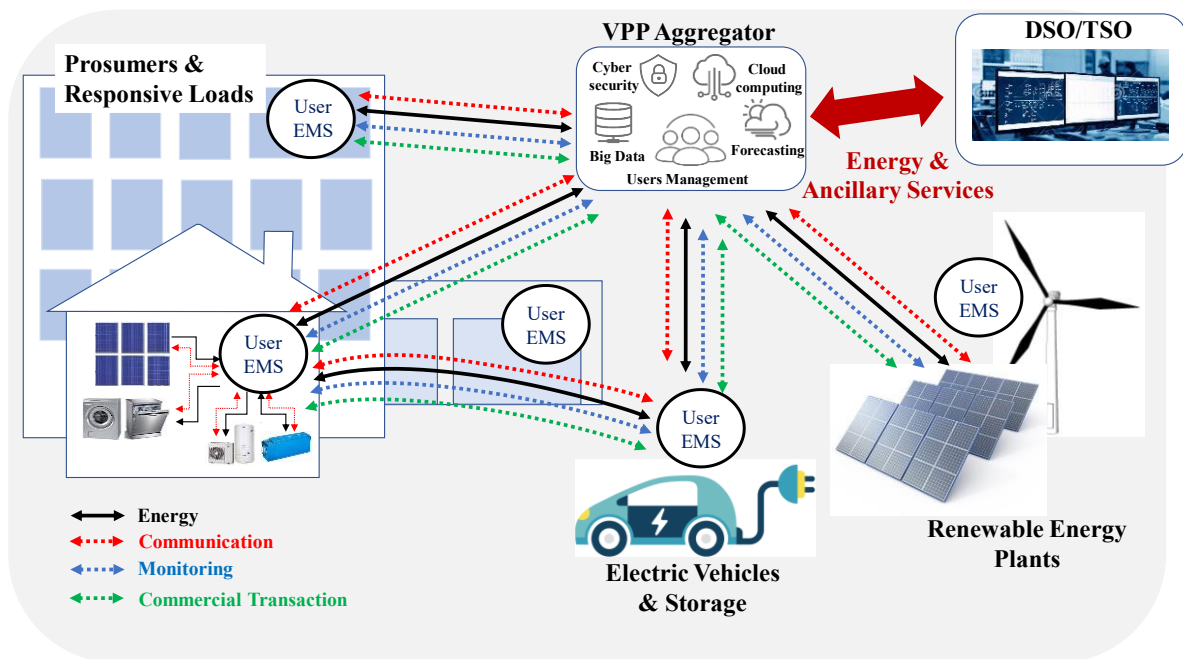
Figure 2. Schematization of a virtual power plant.

Another interesting and promising concept within SDN can be represented by energy hub (EH), namely a common framework that integrates different energy carriers at production, distribution, conversion, storage and consumption stages [3,18]. Therefore, EHs, also called multi-energy systems (MESs), conjugate electricity, heat, cooling, fuels, and transport needs, which can interact optimally to each other at various levels (for instance, within a district, city or region). EHs represent an important opportunity to increase technical, economic and environmental performance of conventional energy systems, whose sectors are treated "separately" or "independently" [19]. It is possible to classify micro EH/MES as residential, commercial, industrial and agricultural depending on their main final usage, each of which has its inherent features in terms of energy carriers, consumption and production. Consequently, different kinds of micro EH/MES can be managed synergistically as a macro EH/MES, in which each system can benefit from the others. The EH/MES concept seems thus going beyond MG because it encloses additional energy carriers, whose integration with electricity production and consumption should lead to further optimization and energy saving. The achievement of all these goals depends however on the employment of suitable EMS designed to manage and control all the system components in a coordinated way.

2.4 Multidisciplinariety in smart distribution network development

As seen in previous paragraphs, SDNs could be strongly interconnected (no radial scheme, no unidirectional power flow) and could be split into small cells or portions, such as MGs or EHs. Consequently, advanced management and control systems and ICT will be needed to manage local cells, control generated and absorbed power, deal with congestions and prevent propagation of overloads and faults. These functionalities rely on the knowledge of the system state and on a continuous and accurate monitoring of the network. Advanced metering, IEDs, and communication infrastructures guarantee the observability of the overall SDN; this is an essential prerequisite for any efficient controllability and MS design should take into account CS and DMS characteristics. ESSs are also crucial, together with the other DERs, in order to guarantee the sufficient level of flexibility.
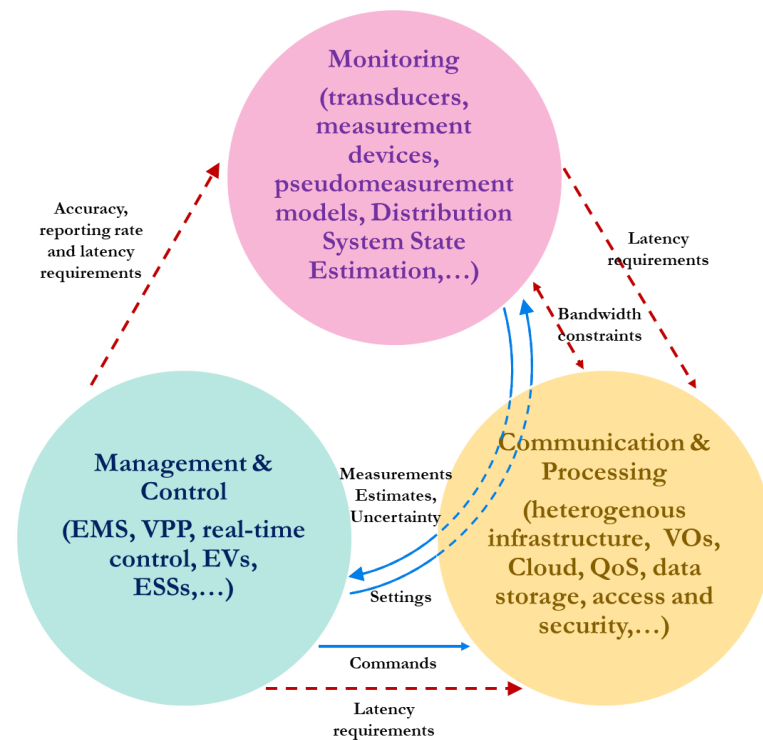
Figure 3. Multidisciplinary interactions in design, development and operation of SDN.

A schematic view of the multidisciplinary key interactions above-mentioned is illustrated in Figure 3, which shows the relationships of the design and operation of SDN in terms of requirements (red dashed lines) and real-time data (blue lines), as well as the strong connections among three main fields: monitoring system (MS), management and control system (MCS) and communication and processing system (CPS). Considering MCS as the core of the SDN intelligence, it is clear that MS represents the producer of input data for the decision process, while CPS is the structure underlying the information exchange and elaboration. The MS includes all the hardware technologies and algorithms to achieve frequent and accurate pictures of the system, both globally and locally. Measurements should be seen in a broader sense as they are the prerequisite for each control method and each service operation. For this reason, the MS must produce real-time data along with a description of their uncertainty to allow the optimization and management activities. Data are thus inputs to DMS and EMS and these applications determine the accuracy, reporting rate and latency requirements for the MS, which can be configured according to the upper level needs. The MS constraints are directly linked to those of the CPS. The CPS design has thus a twofold objective: allowing measurement transmission and elaboration without corruption or degradation of the information and implementing the infrastructure for MCS. In the following sections, a detailed review of all these themes is reported, ranging from the MS to the CPS description, in terms of achievements and challenges.

3. Monitoring of Smart Distribution Networks

Distributed monitoring systems for SDN need to be rigorously qualified from a metrological viewpoint, flexible, secure, able to keep into account communication issues and effectively matched to novel SG applications.

3.1. New generation meters

The new generation meters for electric energy are typically referred to as smart meters (SMs), since they have communication capabilities and they can be integrated with a metering infrastructure that can be considered as "intelligent", aiming at the introduction of new monitoring, management and market paradigms. In Europe, the Directive 2009/72/EC "concerning common rules for the

internal market in electricity" [20] of the European Parliament and Council issued first recommendations for the introduction of intelligent metering systems. In this perspective, strong efforts have been made and, for example, Italy was a forerunner and has thus been playing a leading role in SM installation (35 million of 1st generation SMs were installed starting from 2001 and their substitution with 2nd generation devices is ongoing) [21]. The expected diffusion rate by 2020 is above 90% for at least 13 EU member states.

Such a relevant change in the user monitoring will have a strong impact also on the infrastructure and the applications of SDN, and thus the SM, which is the widespread "sensor" element of the MS, must be accurately designed and appropriately characterized from a metrological point of view. SM characteristics in terms of measured quantities, reporting rate, measurement algorithms and communication protocols are the prerequisite to serve as building block for the technical and economic architecture.

For this reason, in the last years, an intense research activity has been carried on to understand limits and potentialities of commercial SMs under different operating conditions and to foster development and innovation in SM field. In particular, commercial SMs can show metrological problems in the presence of realistic distorted signals for both active and reactive power [22] and the behavior is very different with respect to classic inductive meters [23]. Thus, ad-hoc procedures should be defined for the calibration [24] and it can be important to characterize the SM trying to identify also its operating principle [25].

The new SMs are expected to be easily programmable and expandable due to their processing capabilities. Proposals for open-source meters are available both from academy [26] and community [27]. The availability of single board computers has fostered the design of low-cost customized meters. However, it is important to recall that strict metrological requirements apply to devices that are intended to support commercial energy transactions (see, for instance, harmonization issues in Europe [28]). Moreover, the meter accuracy has to be verified in actual operating conditions, thus asking for new instruments suitable for the onsite calibration of electric energy meters [29].

Beside metrological aspects, it is important to recall that SMs will allow also the implementation of additional functionalities and local control applications, particularly appropriate in a free electricity market context [30]. New paradigms of energy monitoring are necessary to avoid overloading with data, thus event-driven approaches can be exploited [31].

When SMs are considered as part of the overall MS, they can contribute to SDN control at both MV and LV levels [32]. It is important to highlight that, from a multidisciplinary perspective, there is no sharp distinction between monitoring and management. As an example, SMs will allow also the implementation of power quality monitoring functionalities [33,34], actual LV losses monitoring [35], illegal electricity usage detection [36], thus underlining how metrological, control and application issues are strictly tied to each other.

3.2. Synchronized measurement systems

Phasor measurement units (PMUs) represent an emerging technology for power system monitoring [37]. The first attempts to design a device that can measure phasors and, thus, absolute phase angles date back to the 1980s, but it was not until the 1990s that commercial PMU installation started. PMUs have been installed in transmission networks for 20 years and they are becoming a mature technology to replace or, better, to support SCADA systems. PMUs located at different points on a wide area can measure voltage and current phasors, frequency and rate of change of frequency (ROCOF) in a coordinated way, due to the synchronization to a common coordinated universal time (UTC) timescale. PMUs thus output synchrophasors, which are phasors measured at specific time instants (timestamps of the measurements are provided) and include absolute phase angle information. PMUs have unprecedented measurement accuracy and fast reporting rates that allow having continuous snapshots of network conditions [38].

Commercial PMUs are typically required to comply with standard requirements. For instance, the latest IEEE synchrophasors standards are C37.118.1 [39], issued in 2011, and its amendment C37118.1a-2014 [40]. These documents define two performance classes, intended for protection and

measurement application respectively, and give the limits to assess compliance under different operating conditions. Both steady-state and dynamic conditions are considered (among others, oscillations, frequency ramps and step changes), with different requirements depending on the test condition and the set reporting rate. In recent years, many algorithms have been proposed to cope with different characteristics of input signals (see Chapter 3 of [38] for a comprehensive review of recent contributions).

Thanks to their characteristics, PMUs appear as a very promising tool also for MV network monitoring and they are becoming appealing for DNs too. The decrease in their cost is clearly one of the leverages to allow a widespread installation of PMUs. In this perspective, several research projects are dealing with the design of low-cost PMU-like devices that are designed on embedded platforms; this may enable their diffusion even at LV level [41–43]. From a metrological viewpoint, PMUs conceived for SDN applications must comply with different requirements than classic PMUs for transmission systems since lower voltage drops and phase-angle differences are concerned. Furthermore, SDNs are expected to show higher variability and dynamics, due to the penetration of RES and scarcely predictable DERs. For these reasons, PMUs for SDN are high-level instruments and require ad hoc design [44–46] and they are expected to change their targets and specification. In [44,47] the objective of a new generation of PMUs able to have both fast and accurate responses is sought. In [48] the impact of unbalance, typical of DNs, is considered and analyzed. Such PMUs require new characterization procedures and great challenges must be faced when considering the requirements that calibrators must guarantee [49,50].

PMUs are usually considered as stand-alone devices, but new paradigms can be exploited. In a IEC 61850 scenario [51], which is becoming a possible framework for communications also outside the electrical substations, the PMU can be conceived as the union of one or more merging units that acquire and tag samples (sampled values) and an IED that runs the algorithm needed to calculate measurements [52]. PMUs are traditionally equipped with a GPS receiver [37], but synchronization based on packet-network protocols have taken place (see Chapter 5 of [38]), considering both hardware [52] and software [53] implementations of precision time protocol and investigating also wireless connection potentialities [54] and recent White Rabbit synchronization perspectives [55].

PMUs for transmission networks are typically included in wide area monitoring systems (WAMS). WAMS concept must be extended to the SDN context and new architectures must be proposed to integrate synchronized and conventional measurements. Notwithstanding the complexity of this task, one element, the phasor data concentrator (PDC), will be a building block of the system, since it is the routing element of the architecture and allows aligning and checking the incoming streams from PMUs [38]. SDN monitoring and management infrastructure will be built on different communication and computation systems (see Section 4 for a deeper discussion on this topic), depending on the technical and economic constraints of the DSO and of the corresponding regulations. For these reasons, new solutions are needed for a better integration of instrumentation and communication: among other aspects, latency [56] and PMU reporting rates can be managed dynamically [57,58].

PMUs allow building an MS based on a common timescale and thus foster new application of management and control as will be discussed in the next section. Besides, a widespread presence of PMUs will allow applying important measurement procedures that were traditionally performed off-line, such as network line parameter estimation and transducer calibrations [59]. A review of possible applications of PMU in DN can be found in [60]. Among them, it is important to highlight distribution system state estimation (DSSE), whose challenges will be concisely recalled in the next paragraph, since it represents the main outcome of the whole MS [61,62].

3.3. Distribution system state estimation

The knowledge on the status of the network is a prerequisite for an efficient SDN operation. The state (in terms of voltage profile or current/power flows) is provided by DSSE tools. The state estimation is traditionally used in transmission systems where redundant measurements collected from SCADA are available. The classic methods do not apply to DNs because of their intrinsic

peculiarities (unbalanced three-phase systems, largely variable line lengths with low X/R ratios, radial or weakly meshed topology) and of the great variability introduced by DG.

The main problem is nevertheless posed by the lack of measurement devices. An upgrade of the MS is mandatory in order to improve the monitoring and to implement SDN automation. Placement methods should consider both economical and accuracy constraints: for example, both SM and PMU are used in [63,64], considering also possible measurement loss, metrological degradation or network parameter uncertainty [65], while traditional instruments are used in [66,67]. Nevertheless, the DSSE will rely also on pseudo-measurements, which are power consumption/generation data that allow extending the available information on loads/generators and making the system observable jointly with the real-time measurements collected from the field.

Despite the efforts made in recent years to develop DSSE algorithms tailored to the specific characteristics of DNs, many challenges still prevent an easy deployment of DSSE on the field [68]. Attention should be paid to the integration of measurements from new devices, such as PMUs [61] and SMs [69].

SM measurements integration with DSSE requires aggregation and data processing [70,71]. These measurements are susceptible to time delays or temporary loss of data and it is thus necessary to develop load estimation algorithms to replace missing data and estimate future SM measurements. In this context, artificial intelligence (AI) algorithms [72–74] can be applied to estimate missing data and forecast power loads based on past measurements. SM measurements can be helpful also to build pseudo-measurements; this is not a simple task because it involves load and generation forecasting (as in [75], see the discussion in the next section), data modeling and, even though it is often neglected, uncertainty evaluation. Pseudo-measurements are built by means of statistical analysis, AI, and cluster analysis methods [71,76,77], while ad-hoc techniques must be designed to include complex non-Gaussian models in DSSE algorithms [78].

The DSSE, in a SG perspective, should be based on all the available information with the two-fold aim of improving estimation accuracy and complying with economical constraints. For this reason, the DSSE will be based on algorithms able to integrate all measurement types, considering their different accuracy specification, reporting rates and measurement algorithms. Synchronized measurements could support fast linear algorithms [62], but hybrid systems seem mandatory because of the heterogeneity of available data [61]. Different algorithms have been proposed (see [38,79] for a review) considering different choices for the state and the measurement inclusion, but research and development activities are still needed for a large scale application.

Another important aspect is the integration with the communication system. As discussed above, the new generation measurement devices should have high measurement rates and send continuous data streams. For this reason, it is important to design DSSE tools that can adapt to operating conditions and work at different reporting rates [80], because the metrological characteristics of the instrumentation can vary with the actual conditions. Furthermore, multi-area approaches can be necessary to cope with very large DN systems, but synchronization, harmonization and accuracy issues are unavoidable [81,82].

3.4. Forecasting-aided monitoring systems

Short-term electricity demand forecasting is crucial for generation capacity scheduling and maintenance, evaluation of ESS usage, as well as real-time control of building energy systems and optimization of fuel purchase plans. The electricity consumption profiles in commercial and residential buildings are responsible for a significant share of the overall energy demand. Thus, electricity load forecasting models have to be devised for both real-time control and planning of the energy consumptions. In this context, the approaches for the short-term electricity demand forecasting in building can be grouped into three categories: physics-based (white-box), data-driven (black-box) and the so called hybrid (grey-box) [83,84].

The physics-based methods use physical principles to calculate thermal dynamics and energy behavior of the whole building level or for sub-level components. In particular, the physical models are based on solving equations that describe the physical behavior of the heat transfer. They have

been adequately developed over the past fifty years and a comprehensive review of the thermal building models developed and the related applications is given in [83,84]. Although the physics-based models are effective and accurate, expensive knowledge on the physical system are needed in practice to achieve accurate simulation, especially on the mechanisms occurring inside and outside the building geometry. Unfortunately, it is far from being always the case and this lack of precise inputs leads to a low accurate simulation.

In contrast with the physics-based approaches, the data-driven methods have the great advantage of producing a model only from measurements. Since SMs and PMUs provide volumes of data ranging from several hundreds of gigabytes to tens of petabytes (or exabytes), recently the effort in the load forecasting field mainly focuses on data-driven approaches. The corresponding models may be categorized into two groups: statistical-based and AI-based models. The statistical-based group includes regression algorithms, such as auto regressive (AR), moving average (MA), auto regressive moving average (ARMA), and auto regressive integrated moving average (ARIMA) [85–87]. These models are based on classical mathematical theory, thus their behavior is well understood and the model parameters are straightforward to estimate. However, these models tend to work only for energy systems that are well behaved. On the other hand, the AI models are based on expert systems [88], artificial neural networks (ANNs) [89–91], support vector machines, fuzzy logic [92], and genetic algorithm [87]. Currently, the most widely used methods are those based on ANNs, applied in this area since the 1980s. The ANN models are better suited for modelling the complex relationships between building level characteristics and energy consumption since such models have fewer constraints on the statistical relationships among variables. They focus on the variables that are very significant and ignore the information that has little impact on the output. The drawbacks of black-box methods consist of the large amount of data required and, moreover, it is usually difficult to reflect the obtained results to the real world. Still with focus on ANNs, in the last few years deep learning models [93] have boosted to a great extent the number of software applications based on ANNs. Despite the lack of agreement about the motivations that make deep neural networks (DNNs) so effective, DNNs have been successfully applied to a variety of fields, including energy prediction (see, for instance, [94] and [95]). Moreover, models have also been proposed aimed at improving performance through the integration of different AI techniques (e.g., [96]).

It is possible to overcome the limitations of the physics-based and data-driven models by coupling them in a hybrid-model. This can be achieved employing a black-box model as physical parameter estimator or using a black-box method only in a sub-field, where a physical model is not effective and accurate enough. Up to now, limited research has been done regarding hybrid approaches. Nevertheless, the grey models proposed in [97,98] for short term load forecasting have shown high accuracy.

4. Management and Control of Distributed Energy Resources in Smart Distribution Networks

4.1 Energy management systems for distributed energy resources

The IEC 61970 standard defines the EMS as "a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost" [5,99]. Beyond this, EMSs are able to monitor, analyze and even forecast the overall system power profile, accounting for electricity market prices as well. Consequently, based on this information, EMS can optimize the operation from different technical and economical points of view, by guaranteeing the compliance with all system constraints simultaneously. Once the best management strategy has been defined, EMS demands its implementation to suitable hardware and software interfaces, such as SCADA systems, human machines interfaces and local DER controllers [5,100]. EMS for the operation of DERs in SDN will be embedded in DMSs as advanced functions that rely on accurate input data and fast communication signals. For a proper DMS design, the impact of the state estimation uncertainties and of the communication system delays should be jointly evaluated [101].

The EMS can be characterized by either centralized or decentralized architectures. The former class determines the reference signals for all DER local controllers by using suitable optimization criteria and solving procedures. The tracking of the optimal signals is then demanded to local controllers, which do not contribute to the overall system optimization. The drawbacks of centralized EMS are the high computational cost, especially when several DERs are involved, the weak scalability and poor robustness in case of failures [5]. Some of these drawbacks can be overcome by decentralized EMSs, which propose optimal reference signals to local controllers; however, the latter are free to follow or not the suggested reference profiles in accordance with their inherent needs. Decentralized EMSs need bidirectional communications with all system components, which should be synchronized properly, thus leading to increased costs compared to centralized solutions. An alternative and interesting approach consists of distributed or hybrid architectures [5,102], namely a combination of centralized and decentralized structures in which local controllers can communicate to each other and with a centralized control unit in order to define the most suitable reference scenario. As a result, computational complexity is reduced compared to centralized architectures, but communications become more complex [5,102].

Regardless of EMS architecture, the synthesis of suitable reference signals can be achieved by setting appropriate objectives to optimize. A variety of optimization goals can be used, which can be classified in four main categories: economic, environmental, technical and user-driven [103]. Although each of these optimization goals can be pursued individually, they may be also combined to each other by following, for example, a multi-objective optimization (see, for example, Chapter 11 of [104]). In this regard, two main approaches can be followed, namely "single numeric" or "Pareto" [103]: the former consists of combining all the objectives into a single function, e.g. by a weighted sum. This approach has the advantage of simplifying the optimization process, but the results are affected significantly by the choice of the weighting coefficients, which is not a trivial task. Differently, the "Pareto" approach consists of optimizing multiple objectives simultaneously; thus, a priority criterion can be employed, which consists of optimizing all the objectives sequentially [105]. Alternatively, other methods can be used, such as the minmax and the epsilon constraint methods [103]; the former consists of setting a suitable reference signal for each variable to optimize and then minimizing the differences between actual and reference values. The epsilon constraint method consists instead of selecting a main objective and converting all the others into equivalent constraints by defining suitable thresholds. However, the most popular approach is identifying the Pareto frontier and selecting non-dominated solutions [103,106].

The EMS optimization criterion can be satisfied by using a number of optimization algorithms [5,103,107], which can be carried out in advance and/or in real-time depending on the kind of services to provide [108]. The most important optimization algorithms are summed up in Table 1; each of these presents advantages and drawbacks, thus its employment is strictly related to the specific optimization criterion and inherent features of the system to optimize.

Table 1. Main methods for EMS optimization [5,103,107].

Category	Main Methods
Classical and Exact Solution	Linear Programming, Non-Linear Programming, Dynamic Programming, Rule-based, Model Predictive Control
Heuristic and Meta-Heuristic	Genetic Algorithms, Particle Swarm Optimization, Ant Colony Optimization, Simulated Annealing
Artificial Intelligent	Fuzzy Logic, Neural Networks, Multi-Agent System, Game Theory

Generally speaking, classical methods are based on system modeling and parameters, whose accurate knowledge is thus fundamental for achieving suitable and effective solutions. However, these methods are generally high-demanding in terms of both computational resources and execution time [103]. These drawbacks can be partially overcome by heuristic and meta-heuristic algorithms,

but at the cost of achieving sub-optimal or local optimal solutions [103]. AI methods may lead to improved results compared to meta-heuristic approaches, but they require proper training and increased computational effort. Regardless of the specific optimization procedure, suitable forecasting of both electricity production and consumption is generally required in order to enable a proper DER optimization over a given time horizon [109,110].

Some EMSs that rely on optimization approaches are actually being manufactured and marketed by several energy companies, such as Schneider Electric, ABB, General Electric and Siemens [5].

4.2. Energy storage systems for smart distribution networks

EMS optimization discussed in the previous paragraph is generally enabled by several kinds of ESSs [111–113], which can be broadly classified in seven major categories: reservoir or pumped hydro energy storage (RHS or PHS), compressed air energy storage (CAES), hydrogen energy storage (HES), superconducting magnetic energy storage (SMES), flywheel energy storage (FES), electrochemical battery (EB) and ultra-capacitor (UC).

Both RHS and PHS systems have been widely employed for several decades, as proved by the fact that they account for almost the 99% of the energy storage capacity worldwide, 34% of which in Europe [111]. This ESS technology is thus well established and conventionally used to cope with the peak power demand [111]. However, the rapid diffusion of RESs and their related issues makes these systems useful for primary and secondary frequency regulation [112]. Currently, research and development activities on RHS/PHS are focused on improving their dynamic performances and increasing their power operating range by means of variable-speed motor-generator systems [112]. It is worth noting that the use of either RHS or PHS requires an appropriate geographical location, which may increase investment costs significantly [111]. Regarding CAES systems, they represent a relatively well-established technology, especially if large systems are considered [112]. However, CAES is not as widespread as other similar ESS that share the same level of technological development; this is due mainly to siting constraints and high investment costs, which prevent CAES from being economically viable [111]. This issue could be partially addressed by enabling CAES to provide multiple grid services, such as supporting off-shore wind power plants, black start and secondary/tertiary frequency regulation [112]. Further research and development activities are also needed in order to improve the energy conversion process, especially in terms of efficiency [112]. HES systems are very flexible because the stored energy, once converted into hydrogen, can be employed in several different forms (electrical, chemical, thermal, etc.) [111]. HES systems are well-suited to large-scale energy services over long time horizons, such as primary reserve, energy arbitrage and seasonal storage [111,112]. Main drawbacks of HES technology arise from high installation costs, low efficiency, safety issues and the lack of proper infrastructures able to exploit HES potentiality to the maximum extent [111,112].

The SMES systems seem particularly suitable for providing power services to the electric grid, such as voltage/frequency regulations and power quality applications [112]. This is due to several advantages, among which high power density, high efficiency and robustness, high cyclability (in terms of number of charging/discharging cycles) and long lifetime. However, the main SMES drawback consists of very high investment costs, which are related mainly to the cooling system needed for guaranteeing the superconductivity of SMES coils; in this regard, research and development efforts are actually focused on novel superconducting materials able to operate at higher temperature, which would reduce cooling system requirements and costs [112]. Another popular ESS is represented by FES, which is made up of a rotating mass accelerated and decelerated by an electrical machine; this operates in motoring and generating mode alternatively, thus ensuring a bidirectional power flow between the FES and the electric grid. Several FES systems are on the market for different applications (automotive, road and rail vehicles, UPS, etc.) [112]; focusing on power system applications, FES systems are suitable for voltage/frequency regulation due to their weak energy density [112]. In addition, FES systems are characterized by some safety and control issues, especially as far as high rotating speed is concerned (tens of krpm). EB will become the most

used ESS all over the world, although they currently present limitations relating to their relatively short lifespan due to cycling as well as the round trip efficiency [111]. There are several kinds of EB, among which conventional EBs represent a well-established and low-cost technology, but suffer from long charging time, high temperature sensitivity, periodic maintenance, low cyclability and reliability [112]. High-temperature EBs, especially Ni-NaCl, are instead characterized by high reliability and long lifespan, as well as high energy and power densities. Nevertheless, there is the need for keeping high operating temperatures, which require appropriate thermal insulation and heating systems [112]. Better performance in terms of both energy and power densities can be achieved by Li-Ion EBs, which are widespread in spite of their early development stage and high costs [112]. Regardless of the specific technology, EBs are valid solutions for providing energy and, to a less extent, power services. Differently from EBs, UCs present very high power density, high efficiency, fast dynamic responses, high cyclability and long lifetime; these features make them suitable for power services such as frequency regulation and power quality improvement [112]. Main UC weaknesses consist of very low energy density and high costs, which prevent their employment for energy-intensive applications [111].

Based on the all the above considerations, it seems clear that the main issue that prevents ESS diffusion consists mainly of high investment costs, which may not be completely counterbalanced by subsequent economic benefits [103]. This is mainly due to the limited number of energy and/or power services that a single ESS technology can provide, especially for FES and UC. In this regard, a viable and very promising solution is represented by hybrid energy storage systems (HESSs); these combine two or more ESS technologies characterized by complementary features, in order to increase the number of grid services they can provide and, thus, their economic viability [103]. Among all the possible ESS combinations, those made up of EB and UC seem the most promising [114,115]; this is mainly due to their high level of modularity, which enables them to fit different energy and/or power requirements and, thus, to provide multiple grid services simultaneously [116–118].

5. Communication and Data Processing in Smart Distribution Networks

### 5.1. Communication technologies for smart distribution networks

In SDNs, energy consumption and RES production are measured by smart metering systems [119]. The data gathered from the SM are sent through wired or wireless networks to the EMS, which may be also responsible for billing-related functionalities. Based on the level of intelligence and on the provided functionalities, the metering system can be classified as one of the following [119–121]:

- Automated meter reading (AMR)
- Automatic meter management (AMM)
- Advanced metering infrastructure (AMI)

In AMR the data acquired from SMs are sent to a central system every hour, day, week or year. The central system is responsible for analyzing data and performing billing procedures based on real-time consumption data, rather than on an estimated energy consumption. AMM extends AMR functionalities by allowing bidirectional data exchange, therefore enabling limited forms of meter control. Thanks to AMM, demand response programs, which offer time-based rates, can be implemented to encourage users to save energy during peak-demand times. AMI is an evolution of both AMR and AMM towards Internet of things (IoT) systems. AMR and AMM can be considered as subsystems of the AMI. The AMI is defined as the combination of hardware (e.g. SMs, communication media) and software (e.g. the data management system) used to ensure measurement, storage and processing of user's consumption data. AMI provides various interfaces to interact with both users and service providers by using ICT technologies.

Figure 4 shows the typical architecture of an AMI [119,122] able to integrate SMs with other objects inside a smart home, such as energy consuming appliances and RES power generation [123]. These objects are connected within the home area network (HAN). Smart homes belonging to the same neighborhood can cooperate, for example sharing the power generated by a photovoltaic plant. In this case, they form a neighbor area network (NAN).
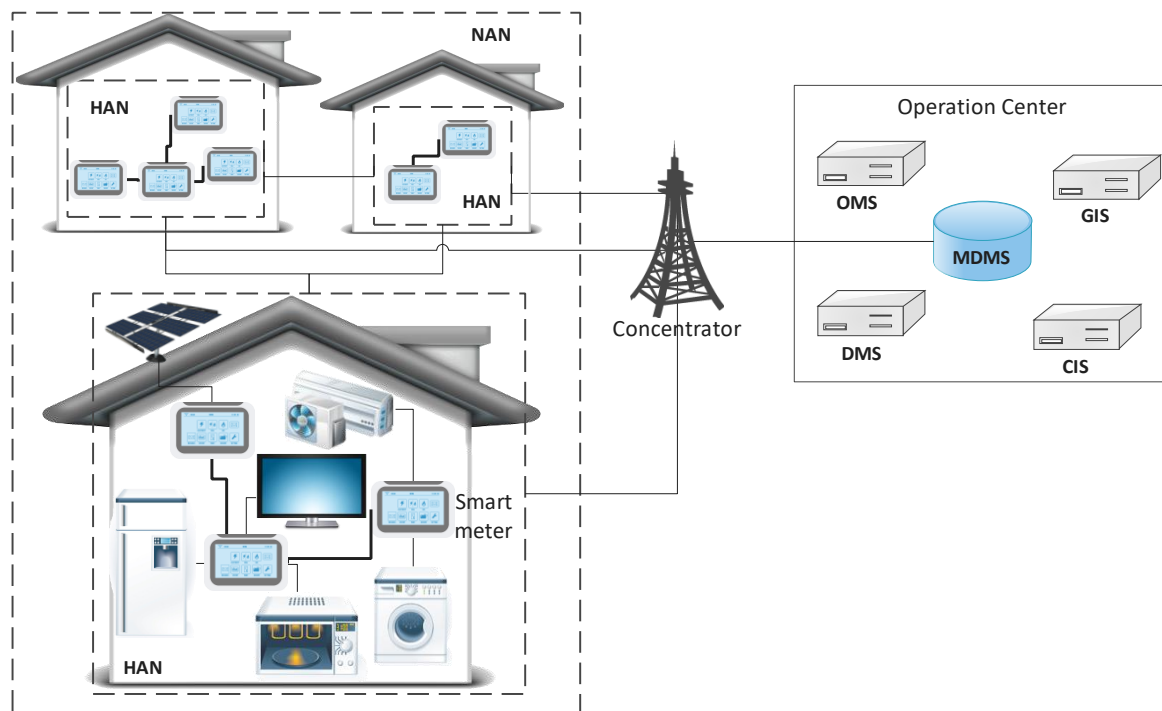
Figure 4. Basic elements of an AMI.

Data collected from HANs and NANs are sent to the closest concentrator, which forwards them to the closest operation center [122]: in case only one central operation center is responsible for the whole system, the AMI is said to be centralized; if each local area network (LAN) is served by one operation center, the AMI is distributed. Each distributed operation center is locally responsible for analyzing and managing data, as well as making decisions. Only summary and required integrated information is sent to the central operation center through a backbone network. This distributed approach offers multiple advantages with respect to the centralized one: not only it reduces communication overhead and saves communication resources, but it also improves stability and resilience to noise and interferences, thanks to shorter communication distances [124].

The core of an operation center is the metering data management system (MDMS) [119,122,125]. It is responsible for analyzing and storing metering data, controlling SMs remotely, and performing billing operations. Furthermore, the MDMS provides interfaces with the following functional elements of the operation center:

- The outage management system, which detects, manages and registers power outages;
- The geographic information system, which provides geographic information about the location of the elements of the SDN;
- The consumer information system, which manages information about the consumer, such as consumption rates and billing-related data. It enables the development of new products and services, based on the consumer profile;
- The data management system, which provides control, management and forecasting functionalities.

The whole AMI is based on data that are collected from SMs and sent through wired and wireless communication media to operation centers, where they are stored and processed so that decisions can be made and sent back to the consumer's premises. In the following, the main communication standards used in SDNs will be surveyed in Subsections 5.1.1 and 5.1.2. Table 2 summarizes the main characteristics of these standards.

Table 2. Characteristics of main communication technologies used in AMI.

Technology	Standards	Data rate	Frequency band	Communication range	Network
NB-PLC	IEC 61334, G3-PLC, PRIME, ITU-T G.HNEM, IEEE P1901.2	Single carrier: tens of kbps. Multicarrier: <500 kbps	3÷148.5 kHz (EU: CENELEC band 3 – 148.5 kHz)	>150 km	NAN, LAN, WAN
BB-PLC	IEEE 1901, ITU-T G.9960/61, HomePlug	<200 Mbps	2÷86 MHz	<1.5 km	HAN
Fiber optics	IEEE 802.3ah, ITU-T G.983/984	<10 Gbps	~186÷236 THz	<60 km	WAN
WSN	IEEE 802.15.4 (ZigBee)	<250 kbps	2.4 GHz EU: 868 MHz USA: 915 MHz	<1600 m	HAN, NAN
WiMAX	IEEE 802.16	<1 Gbps	Typically 2.3, 2.5 and 3.5 GHz	Good: 0÷30 km Bad: 30÷100 km	NAN, LAN, WAN
Mobile communication	2G, 3G, 3.5G, 4G, 4.5G, 5G (expected)	<1 Gbps	Typically 700, 850, 1800, 1900, 2100, 2300, 2600 MHz	Good: 0÷30 km Bad: 30÷100 km	LAN, WAN

5.1.1. Wired communications in smart distribution networks

A wired communication media frequently-used in SDNs (particularly in AMI) is the power line communication (PLC), since it combines the electric power distribution line with the data signal [119,126]: PLC acts by modulating carrier signals directly on the power cables. PLC represents an alternative broadband networking infrastructure without installing dedicated and expensive network wires such as twisted pair cables or fiber optics. The main disadvantage of PLC is that it suffers from multiple types of interference: since the power wiring is unshielded and untwisted, it acts as an antenna, thus causing an interference to the existing users of the same frequency band and receiving interference from radio signals. Improper wiring and circuit breakers along the line cause noise and connection interruptions, respectively. Moreover, when the interruption of electric service occurs, there may also be the interruption of the communication channel between the ICT devices. Furthermore, security issues can arise since the signal carried along cables could be easily intercepted and, thus, cryptography is needed. Nevertheless, PLC high availability, cost effectiveness and ease of installation and management have contributed to its widespread usage. There are two major PLC technologies that operate at different bandwidths: narrowband PLC (NB-PLC) and broadband PLC (BB-PLC) [127,128].

NB-PLC, which operates in the 3÷148.5 kHz frequency range, is characterized by low data rates (up to 500 kbps) and long distances (more than 150 km). It is mostly used for appliance control. BB-PLC is used for applications that require higher data rates (up to 200 Mbps on very short distances). It operates in the HF/VHF frequency bands (1.8-250 MHz) and it is not able to cover more than 1.5 km. It is typically used for high data-rate in-home networking applications.

It is worth to mention that also the fiber optic technology can be used in SDN as wired communication media [129]. Since it provides high data rates and ensures reliable communications, it is mostly used to connect concentrators and to provide communication between concentrators and control centers. It has many advantages such as data transmission over long distances and low losses,

but it is much more expensive compared to PLC solutions and it is better suited to backbone or substation connections.

5.1.2. Wireless communications in smart distribution networks

Along with PLC, the main communication media used in SDN are expected to be the wireless media, because of their typically low installation costs and the easy design of the network. In this regard, the WiMax is an option for wireless communication media within NANs and LANs [130] and its performance in an active DN management are assessed in [101]. It is defined by the IEEE 802.15.6 communication standard for broadband wireless communications. It works in the microwave frequency band at 2÷66 GHz, and it is characterized by low latency (lower than 100 ms round trip time), lower deployment and operating costs with respect to fiber optics, and availability of traffic management tools to ensure a good quality-of-service (QoS). Furthermore, data exchange is secured by appropriately designed protocols, such as advanced encryption scheme.

Latest mobile communication technologies are a the most promising choice for communication between SMs/IEDs and the DMS/EMS since they support wide coverage, low latency, high throughput and QoS differentiation. In particular, 5G/long term evolution (LTE) networks are envisioned to be highly used in the near future, thanks to their high data rates, high availability and low energy consumption [130–132]. In high density device grids, such as SDNs, where a large number of devices are connected to a network, 5G facilitates the data exchange from the remote devices, with statistical observations and analysis, allowing their analysis in real time to optimize the energy distribution [133]. 5G will guarantee such requirements with very large bandwidth, high-speed connection and low-energy consumption. Despite the frequency bands are not assigned yet, it is supposed to operate in the mm-wave band. Signal attenuation at such frequencies requires high gain antenna system, which leads to the introduction of antenna arrays [134]. The integration of the array in the generic device is allowed by the small wavelength at the frequencies involved. In addition, array antennas allow the application of beam steering techniques. By exploiting a very short beam sweeping time (10-100 us), such antenna systems simulate an omnidirectional radiation pattern and allow the communication with the surrounding devices [135].

Wireless sensor networks (WSNs) can be widely used for load monitoring and local component interactions (e.g. for distributed network management applications) because of their ease of installation and management, along with the low complexity and low deployments costs. The reference standard for low-rate low-power WSNs is the IEEE 802.15.4 [130], whose most used protocol is the ZigBee. It operates at different frequency bands: 868 MHz in Europe, 915 MHz in the USA and 2.4 GHz worldwide. It is characterized by low data rates (up to 250 kbps) and low communication ranges (up to 100 m).

In general, the different parts of the communication network have different features and capacity; this reflects in the choice of the best antennas for wireless communication. Terminal nodes of the network have to collect and transmit a small number of signals from the sensors. Moreover, such components are likely to be placed in random positions with respect to the antenna, so that an omnidirectional radiation allows collecting all the information and a large bandwidth may not be needed. Differently, in backhaul networks, the antenna needs to transmit a large set of information collected from the terminal nodes. Such links need a higher capacity, which leads to a larger bandwidth requirement. Moreover, the lines of sight between the nodes are permanent, so directional antennas are preferred.

The new devices development requires components increasingly small and economical. Since the antenna dimension has a direct influence on their performance, such a requirement is a strong constraint for antennas too, especially at low frequencies: for instance, bandwidth requirements imply antennas with considerable size, which complicate their integration in wireless and mobile devices [136]. In systems with a small amount of information exchange among devices, such as SMs, the bandwidth is not a stringent requirement and the design can focus on miniaturization while keeping a good radiation efficiency [137,138]. Miniaturization facilitates the integration of antennas with the device, but this affects the resonant frequencies due to metallic parts of battery and case and,

thus, such issue must be considered at the design stage. On the other hand, when a large bandwidth is required, the miniaturization is constrained by the physical limitations. The trade-off between large bandwidth and miniaturization is currently a hot research topic, and strategies as the mode coupling in a folded geometry have been proposed [139].

The different communication systems in SDN are allocated to different frequency bands. As it is well known, the wavelength of the carrier signal determines the choice of the antenna most suitable for the purpose. The advancement of new wireless technologies raises the need for new antennas to cover the bandwidth requirements. Some technologies as WLAN and some channels of Zig-Bee share the same band, so they can be supported by the same antennas. However, the new smart devices need the interoperability among different technologies as WLAN, Zigbee, LTE and WiMAX [140]. Consequently, suitable multiband antennas are required for enabling the development of integrated devices that exploit the potentialities of the different communication standards. Planar monopoles are an easy and widespread solution to mediate between compactness and radiation performance. Printed monopoles with proper modifications can guarantee ultra-wide band performance suitable for IoT with a very small area [141]. In [140] a dual-band fractal monopole antenna based on Sierpinski Gasket to cover ZigBee and WLAN bands is proposed. Such an antenna has an omnidirectional radiation in the horizontal plane in both bands, making it suitable for multi-standard devices in wireless communication. Regarding LTE base-stations, microstrip antennas are suitable when a dual-band operation is required [142]. In [136] a planar antenna system, which supports LTE and ZigBee communication in addition to traditional mobile phone bands, is presented, whose compact size allows its integration in mobile devices. Compact monopoles are attractive for WiMaX band too. In [143] a patch is optimized to cover all these bands with an omnidirectional pattern, allowing the mobility of the device. In [144] a WLAN/WiMAX antenna, which exploits a microstrip-slot and a reflecting plane, is proposed. In [145] a low-profile folded dipole array provides a high gain in the WLAN (~15 dBi) and WiMAX (~17 dBi) dual band with a low cross-polarization and a directional radiation pattern. Table 3 summarizes the cited antenna solutions for the different wireless communication technologies used for SDN.

Table 3. Antenna solutions for SDN.

Antenna	LTE	Zig-bee	WLAN	WiMAX
Planar strips	X	X	-	-
Monopole	-	X	X	X
Microstrip	X	-	X	X

5.2. Data security for the future of smart distribution networks: biometric technologies

According to the Energy Independence and Security Act (EISA), "Cybersecurity for the Smart Grid requires an expansion of this focus to address the combined power system, IT, and communication systems in order to maintain the reliability and the security of the Smart Grid to reduce the impact of coordinated cyber-physical attacks" [146]. The focus of EISA is related to IT security, which must take care of the protection of confidentiality, integrity, and availability of "information and information systems from unauthorized access, use, disclosure, disruption, modification, or destruction" [146].

Since the goal is to bring modern IT network into SDN to improve the efficiency in the energy distribution, a set of issues related to network vulnerabilities and related hacking trials must be taken into account. As reported in [147], the "Stuxnet" malware menaced the security of several Iranian nuclear plants by profiting the fact that the default password of a popular brand of PLC remained unchanged during years. A list of cybersecurity problems was also listed in [147–149].

Among others, managing the protection of cryptographic keys appears one of the most important problems. As a matter of fact, these keys, which assure the possibility of controlling the majority of crucial SDN operating characteristics, are often shared among multiple users, thus the access to the SDN core is exposed to significant security threats. In order to improve the protection level of such core-aspects, biometric technologies were proposed [147,148,150].

Biometrics are physiological or behavioral human characteristics which allow distinguishing subjects among others by the development of an appropriate statistical and/or structural pattern recognition approach [151]. The most widespread biometric traits are the fingerprint, the face, the iris. Recently, the palmvein and the retinal scan of blood vessels have been also proposed as high-security biometrics. A plethora of works about the effectiveness of biometrics has been proposed in the last decades. The presence of many public and private companies aimed at selling biometric products (fingerprint sensors, facial recognition systems and so on) and the market prediction on the investments on such technologies performed by several consulting agencies [152,153] point out the widespread interest on this technology, not only from an academic but also from a market point of view.

With regard to the SG paradigm, [150] describes a possible biometric-based module. Typically, a biometric authentication module is made up of: (1) a capture device able to transduce the biometric trait into a signal that can be treated by signal processing algorithms in order to isolate the basic information from the "background"; (2) a feature extraction module, which takes as input the signal provided by the sensor and extracts from it a set of statistical or structural measurements able to characterize the uniqueness of the signal coming from a certain subject with respect to those of all other possible subjects; (3) the comparator module, which aims at comparing two features sets, and providing a degree of similarity between them, usually called matching score; (4) the decision module, which states, according to the computed matching score, if the compared signals belong to the same subject. In order to make a biometric authentication operating, it is firstly necessary to "enroll" the biometrics of the users who must have access to the SDN. This step requires that all members of this "user population" release their biometric. For each user, a set of one or more biometric signals is processed and stored, as "template" in the system database. During system operation, the user willing to access to the network must release his biometric once again. This novel set of measurements is compared with templates, and the final decision is taken. For example, the percentage of correct recognition rate of several biometrics is reported in [151]: the fingerprint, the palmvein, the iris are among the most effective means to ascertain the identity of a given subject. In particular, these biometrics exhibit significant properties of system scalability, thus maintaining the same level of performance regardless of the growth of the user population. Recently, even biometric authentication and recognition systems have been analyzed in terms of possible vulnerabilities [154]. The most common vulnerability is called "presentation attack" or "spoofing attacks", and consists in submitting to the biometric system an artificial replica of the biometric trait [155]. Therefore, the design of effective presentation attacks detection systems has become a novel and challenging research field. The most investigated biometrics have been mainly the fingerprint and the face, but all possible traits have been analyzed according to the level of their exposition to presentation attack [155–157]. This has led, in the last years, to the definition of accurate and effective experimental protocols, collection of data sets and design of algorithms in order to compare and assess different solutions and also to verify the related advances of the scientific and technological state-of-the-art on "intrinsically robust" biometric recognition systems. In the opinion of the Authors, these advances will make biometric technologies promising for empowering the security level of information of the data stored and managed by SDN, according to what stated by EISA document.

6. Concluding remarks

The paper has presented the challenges in the design, development and operation of the future electric distribution networks, which must become "smart" in order to tackle the issues posed by the massive introduction of RES.

The paper has revealed the need for looking at the SDN design in a multidisciplinary way in order to build the new management applications and to create a consumer-centered system that relies on an accurate and efficient monitoring system and on a reliable communication system. Those ICT infrastructures cannot be defined without the knowledge of the requirements of DMS and dependently from their specific application targets (power delivery network, communication, monitoring, data processing, etc.). The relationships are so strong that the impact of incorrect sub-

system definitions can be dramatic on the overall SDN performance; in this regard, the paper has shown that larger efforts should be made to integrate the concurrent systems even from the early stages of the SDN design as a whole.

The multidisciplinary approach, which brings together the design of information and communication technologies with the electrical network, while keeping also into account cyber-security issues, can help the distribution system planners to design an SDN that is scalable and future-proof during system engineering for greenfield and brownfield projects.

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