Chapter

Introductory Chapter: Open Problems and Enabling Methodologies for Smart Grids

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1. Introduction

Modern power systems are facing several challenges related to the transition from a traditional, fossil fuel-based, and vertically integrated architecture to a smart, sustainable, renewable generation-based, and deregulated system. Smart grid is the key concept that allows this transition and enables a series of innovative applications thanks to the integration of information and communication technologies into power systems.

Smart grids involve two-way electric and information flows across generation, transmission, distribution, and utilization systems, to improve their efficiency, sustainability, reliability, and resilience compared to traditional grids. The attribute "smart" reflects the layer of intelligence added to the power system that is able to *sense* power system's conditions, *interact* with producers and users, and *react* to any unexpected conditions.

Figure 1 describes the main differences between traditional and smart grids [1–3]. The concept of a smart grid was developed in order to reach a set of goals:

- ***Sustainability***: smart grids facilitate the introduction of sustainable and clean technologies, such as distributed renewable energy generators, into power systems.
- ***Monitoring***: smart grids guarantee real-time observability of power systems, thanks to the capillary distribution of smart meters and advanced sensors.
- ***Adaptability***: smart grids can adapt to different and evolving power system's configurations and promote the development of innovative applications.
- ***Resilience***: smart grids improve power system's robustness to disruption caused by natural disasters, extreme weather, and unexpected faults, enabling self-healing.
- ***Transparency***: smart grids guarantee secure and transparent communications and information systems, allowing customers to take keen choices and to proactively interact with the system.

In order to support the evolution of existing power systems from static and hierarchical networks to decentralized and self-healing systems composed by cooperative and self-organizing energy resources, a commonly accepted framework must be established. To this aim, in this chapter the most promising enabling technologies will be presented, and the possible research directions aimed at

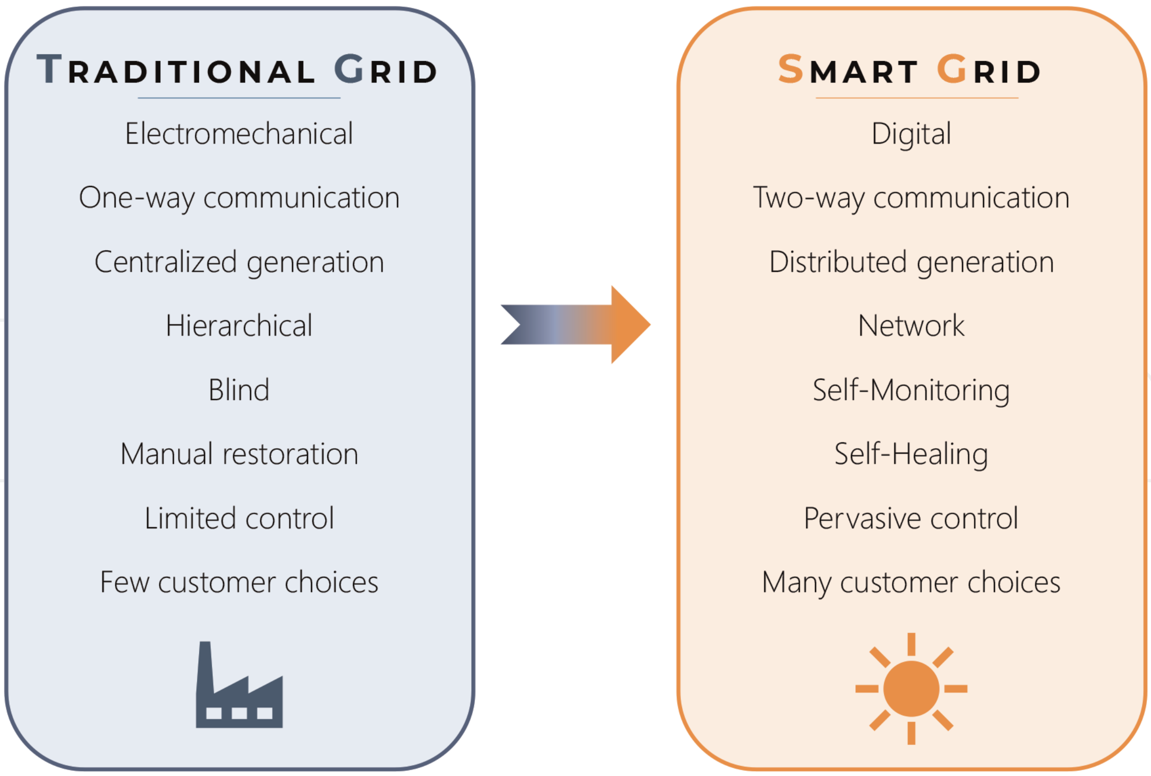

Figure 1.
Comparison between traditional grid and smart grid [1].

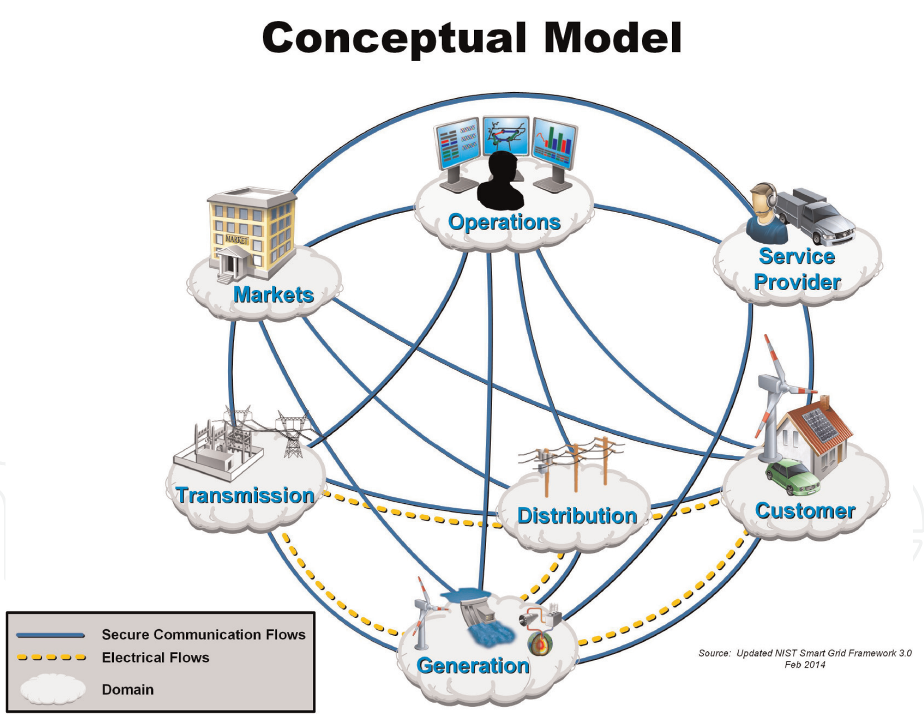

Figure 2.
NIST conceptual model [4].

addressing some challenging open problems, which could hinder their deployment in existing power grids, will be outlined (**Figure 2**).

2. Conceptual model

The most widely accepted smart grid's conceptual model has been developed by the National Institute of Standards and Technology (NIST) (**Figure 2**) [4].

It distinguishes seven different functional areas in smart grids, called *domains*. Each domain is characterized by a set of *actors* and *applications* that perform actions on energy and data inside the domain and allow the exchange of power and information between domains, by means of different *interfaces*, also called *domain gateways*.

The next sections describe the main features of each domain and the related key technologies.

2.1 Bulk generation

This domain collects all the actors and the applications related to the centralized generation of large amounts of power, optimally dispatched in order to satisfy the predicted demand. In traditional power systems, characterized by one-way power flows, this was the only domain in which power was produced.

The importance of this domain is not only due to the production of a high percentage of the total required power but also due to the ancillary services it offers in order to maintain stability and security of the whole power system.

This domain has communication interfaces to market, operation, and transmission domains, although it is electrically coupled only to transmission network.

2.2 Transmission domain

Transmission infrastructures allow the efficient transfer of electrical power from generators to distribution systems. Their main components are high-voltage power lines, substations, sensors, and protection systems. Their correct operation and maintenance is entrusted to transmission system operators (TSOs). The evolution of power systems toward smart grids is leading to the development of several innovative technologies to improve power transmission's reliability and efficiency [5]. The most impactful ones are advanced power electronic-based systems, such as flexible AC transmission systems (FACTS), that enhance controllability and increase power transfer capability of transmission systems.

2.3 Market domain

Market domain is where prices for power exchanges are established. Currently, electricity markets are changing in order to fully exploit the possibilities introduced by future smart grids.

Market domain is connected by communication paths to every other domain. It receives information regarding system's state and constraints by the operators and service providers and proceeds to dispatch generated power in order to satisfy the demand.

Communications between market domain and the other ones must be secure, reliable, and transparent and with low latency in order to correctly operate the system.

Future power systems include a more active participation from the customer's side, thanks to the integration of demand-side management paradigms or the aggregation of various distributed generation and loads in the so-called virtual power plants.

2.3.1 Virtual power plants

Virtual power plants (VPPs) are a smart management paradigm consisting in coordinating generating units with different characteristics, stochastic or dispatchable ones, flexible profitable loads, and storage units in order to maximize the total profit [6]. Generation and consumption are managed in such a way that the market sees VPPs as a single flexible power output toward the grid.

The need for this new energy management paradigm is a consequence of the uncertainty and unreliability introduced by the diffusion renewable energy sources, in particular wind and solar power.

Introduction of a VPP leads to less risky and more efficient bidding in electricity markets, since bad predictions of renewable production can be adjusted by dispatchable generators, flexible loads, and energy storage. Furthermore, this paradigm allows the indirect access of renewable energy sources to the ancillary service markets, increasing their potential integration in power systems.

From the point of view of network operators, VPP simplifies system's management, since uncertainties and imbalances are locally addressed by the aggregator, which can assure a secure or at least less uncertain power production.

2.3.2 Demand response

Demand response refers to the active participation of customers to power system's balancing, requested by grid operators. Customers are encouraged to modify their load pattern by changes in price of electricity or incentive payments [7].

The transition toward smart grids is an essential element for the development of the demand response paradigm, since it requires advanced monitoring, communication, and control systems, in order to be correctly implemented in future power systems.

From the customer's point of view, the participation in a demand response program requires one of the following actions:

- *Load curtailment:* the customer simply reduces its load, accepting the consequences of this reduction.

- *Load shift:* the customer shifts the energy consumption to a different time interval.

- *Local generation:* the customer produces the energy needed locally, reducing its dependence from the grid.

Market operators can act on the demand response using different strategies that can be classified in three main branches:

- *Price programs:* customers pay time-varying prices during different periods of the day. The highest price is during the peak hours, while the lowest is set for off-peak hours.

- *Event-based programs:* customers are rewarded for changing their load upon request. Demand reduction signals may be sent to the participating customers that can voluntarily change their absorbed power in order to get the established incentive for a particular event.

- *Bid-based programs:* different customers send demand reduction bids, consisting in the amount of reduction capacity and the correspondent price. Depending on the bids, the cheaper ones are chosen.

Demand response has several benefits related to different domains. Customers participating in demand response programs have direct economical rewards;

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however, all other customers benefit from the lower prices due to diminished demand peaks. Market performance is improved due to the lower market power of the producers, and operators have another flexible tool to address power systems' technical problems.

2.4 Operation domain

Operation domain is the set of actor and applications required for the reliable, safe, and efficient operation of power systems. The main duties are related to planning, monitoring, protection, maintenance, and control of power systems. The increasing diffusion of distributed renewable energy sources is posing a series of challenges to operators. Traditional power systems were designed for one-way power flows, while in modern grids, backward flows are frequent. Furthermore, the intermittent nature of solar and wind energy requires special attention to avoid system's imbalances and stability problems.

Smart grids are improving operators' capabilities with advanced technologies.

2.4.1 Wide area monitoring systems

Wide area monitoring systems (WAMS) are an emerging paradigm, involving the utilization of system-wide information to prevent the propagation of large disturbances, increasing the efficiency of the transmission system, and providing better protection and control [8]. Their development was possible thanks to the diffusion of advanced measurement systems: the phasor measurement units (PMU) that are the basic elements of WAMS.

The main difference between these sensors and the supervisory control and data acquisition (SCADA) systems is that they are all synchronized to a common reference time, and thus they can measure and compare the phase angles from voltage phasors of busses contained in a wide area control region. They allow a series of useful applications: state estimation, voltage stability control, dynamic thermal rating, congestion management, and fault localization.

The path toward a smarter grid implies the deployment of WAMS in power systems worldwide.

2.4.2 Smart meters

Smart meters are advanced energy meters that offer a wide range of functions, such as storage of detailed consumption data, two-way communication with utilities, and support for dynamic pricing, enabling demand response and monitoring of power quality and disturbance events. A proper deployment of such systems requires an automated metering infrastructure (AMI) that is a two-way communication network linking a huge number of smart meters.

Through AMIs, utilities can improve their analytic capabilities and operate systems in a more efficient, economic, and reliable way. Despite the benefits, AMIs could expose the system to a series of cyber security and customer's privacy threats; thus, they must be carefully designed in order to ensure the protection against cyberattacks.

2.5 Distribution domain

Distribution domain is electrically connected to the transmission domain and to the customer's domain. It is at lower voltage levels, and it is where most of the distributed generation has been installed during the last years.

Until the last decade, it was the least smart domain and the source of most of power outages and disturbances, due to the lack of monitoring and control capabilities. Smart grid transition is starting right from this domain, with a large deployment of smart systems, coupled with two-way communication links.

An evolving concept related to distributed generation, smart monitoring, and controls are microgrids.

2.5.1 Microgrids

Microgrids are smart interconnected networks of loads and distributed energy resources that can work connected to or separated from the electricity grid. They integrate a series of intelligent functions and pervasive controls, in order to be self-consistent [9].

They are characterized by six main components:

- *Power plants:* they can be dispatchable plants, such as low-power, fossil-fuel-based generators that recover waste heat, i.e., combined heat and power (CHP) systems or renewable generators, such as wind and solar plants.

- *Smart loads:* there can be residential, commercial, or industrial loads. In the case of microgrids, flexible and smart loads that can automatically control the absorbed power are preferred in order to better manage the whole system.

- *Energy storage:* storage systems are required to fully exploit renewable energy potential and to provide greater flexibility to the system.

- *Smart meters and sensors:* to keep the system working reliably, a huge amount of data related to different electrical quantities is needed for proper control.

- *Communication infrastructure:* to exchange information and commands between different elements.

- *Central management system:* data collected from microgrid's elements must be processed to take appropriate decisions by a central energy management system that sends command messages to all controllable devices.

Microgrids represent a gradual evolution from traditional grids to smart grids. Their control capabilities can ease grid operators' work, thanks to the local management of the system.

2.6 Service providers

Service providers deliver new and innovative services to producers, distributors, and customers. This domain is connected through communication flows to customer, operation, and market domains.

When delivering services, they preserve cybersecurity, reliability, stability, integrity, or safety of the electric power network.

Examples of these services are:

- *Customer management:* Managing relationships between customers and other power system's actors

- *Energy management:* Monitoring and controlling energy efficiency and demand of customers

- *Aggregation:* Aggregating different customers and producers and efficiently managing the system as a whole, enabling new paradigms such as virtual power plants

2.7 Customer domain

Customer domain is what defines the goal of a smart grid. This domain can be divided into three subdomains, each of which collects different customers with similar behaviors and energy needs: industrial, residential, and commercial. It is electrically connected to the distribution domain.

With the introduction of distributed energy sources, the customer is evolving to a *prosumer*, i.e., it both produces and consumes energy, and it has an active role in power systems.

Most of energy efficiency policies are addressed to this domain, and automation is playing a big role in reshaping it.

Key and innovative concepts for the customers of the future are demand response, described earlier, vehicle to grid (V2G) and energy hubs.

2.7.1 Vehicle to grid

Electrical vehicles are expecting to take an important place in vehicle market, due to the increasing focus on sustainability, energy supply security, and climate change. They have the potential to serve electric grid as dynamical energy storages. Since they are parked most of the time, they can remain connected to the grid [10].

Vehicle to grid is a concept that enables electrical vehicles to interact with power systems, in order to provide a series of functions to support the grid, such as peak power shaving, spinning reserve, voltage, and frequency regulation. Such opportunities are provided by electric vehicles through charging and discharging of their battery packs.

Their integration into power grids has to be carefully evaluated in order to avoid technical problems in distribution systems.

One of the most promising strategies for the integration of vehicle-to-grid technology is the aggregation of electrical vehicles to the virtual power plant or microgrid concepts, in such a way that energy flows are optimally controlled, taking into account power system's constraints, thus reducing eventual stress on the grid.

2.7.2 Energy hubs

A novel concept, potentially introducing further flexibility into power systems, is that of energy hubs.

An energy hub is a unit where multiple energy carriers, such as natural gas and electric energy, can be converted, conditioned, and stored. A typical example of converter is the CHP generator that produces both electric and thermal energy, taking natural gas as input [11].

The main advantages of energy hubs are the increased reliability of supply and higher flexibility. Such concept would add another choice to the participants to demand response, maintaining the same absorbed power but switching the primary energy source from electrical energy coming from the grid to another carrier, such as natural gas. In that case the customer would get the benefits of the demand response incentives without renouncing the part of the absorbed power.

Strictly connected to the concept of energy hubs is the energy interconnector, that is, the integrated transportation of electrical, chemical, and thermal energy, in a single underground device.

3. Conclusive remarks

The large-scale deployment of the smart grid technologies could lead existing power systems to evolve from static and hierarchical networks to decentralized and self-healing systems composed of cooperative and self-organizing energy resources. To this aim, in this chapter the most promising enabling technologies have been presented, and the possible research directions aimed at addressing some challenging open problems, which could hinder their deployment in existing power grids, have been outlined.

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