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Review

Application of Wireless Sensor and Actuator Networks to Achieve Intelligent Microgrids: A Promising Approach towards a Global Smart Grid Deployment

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Abstract: Smart Grids (SGs) constitute the evolution of the traditional electrical grid towards a new paradigm, which should increase the reliability, the security and, at the same time, reduce the costs of energy generation, distribution and consumption. Electrical microgrids (MGs) can be considered the first stage of this evolution of the grid, because of the intelligent management techniques that must be applied to assure their correct operation. To accomplish this task, sensors and actuators will be necessary, along with wireless communication technologies to transmit the measured data and the command messages. Wireless Sensor and Actuator Networks (WSANs) are therefore a promising solution to achieve an intelligent management of MGs and, by extension, the SG. In this frame, this paper surveys several aspects concerning the application of WSANs to manage MGs and the electrical grid, as well as the communication protocols that could be applied. The main concerns regarding the SG deployment are also presented, including future scenarios where the interoperability of different generation technologies must be assured.

Keywords: Wireless Sensor and Actuator Network; microgrid; Smart Grid; communication technologies

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1. Introduction

The raising need of energy, the diminution of the fossil resources and greenhouse effects imply the necessity to find complementary energy sources. A part of the solution is offered by renewable energies but their integration in the electrical distribution grid is still challenging.

The classical power grid is based on large power plants and unidirectional flows toward the consumers. Renewable energies are inherently distributed (in opposition to centralized power plants) and this fact can modify the energy flow in the grid [1]. The integration of the distributed generation (DG) will affect the power quality (mainly by voltage dips induced by failures) and increase the voltage in the entire grid (by the injection of active power). The voltage can be brought back to the normal value by the absorption of reactive power. Those effects are linearly dependent on the level of penetration of DG.

Smart Grids (SGs) are seen as the next-generation of the electrical power system that will be able to provide a reliable and secure grid as well as efficient and cost-effective energy generation, distribution, and consumption [2]. All these targets can be made possible only in the presence of an adapted communication infrastructure that will support data transfer and information exchange in the SG.

The Smart Grid must be able to support a big part of the energy production from high variability renewable sources such as wind turbines and solar panels. Higher levels of stability and efficiency of the grid can be achieved by the management of the generation and also of the demand [3] and the storage. Grid operators will deal not only with large-scale power plants (at least some MW), but also with the increasing number of small installations (such as solar rooftop panels) that are locally distributed. The number of domestic appliances is also high enough to make difficult any attempt of centralized real time management procedures.

A solution can be the implementation of virtual power plants that employ the communication opportunities offered by the Smart Grid or the development of microgrids (MGs) based on geographical proximity [4]. Both models can include small power generators, loads and energy storage systems. The SG will see the virtual power plant or the MG as an entity capable of supplying (selling) or absorbing (purchasing) electrical energy. The principal difference is the connection to the main grid. The elements of the virtual power plant can be connected anywhere on the grid, even at different voltage levels, offering thereby a higher flexibility. Inversely, all the elements composing the microgrid share the same connection to the main grid. Undoubtedly, this is a limitation for MGs but, in exchange, it makes possible the islanding capability. Virtual power plants will use the communication network of the SG, increasing unavoidably the data flow. On the other hand, MGs can use a cheaper local communication network for its own management purposes, reducing data load and congestion of the main network. The rest of this paper will survey the behavior and requirements of electrical MGs to become real actors that will transform the mains into an intelligent electrical grid. In this context, Wireless Sensor and Actuator Networks (WSANs) constitute a promising technology that will contribute to this evolution towards a Smart Grid scenario. As an example, Figure 1 shows a SG infrastructure including a MG and a WSAN, which transmits the necessary information to achieve a correct management of the whole system.

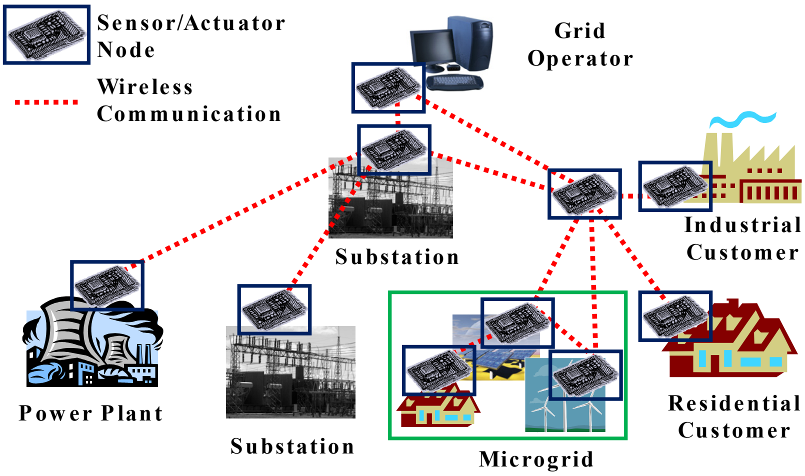

Figure 1. Example of a Smart Grid (SG) infrastructure including a Wireless Sensor and Actuator Network (WSAN).

This article is structured as follows. Section 2 deals with the different management techniques for MGs, including Demand Side Management (DSM), to illustrate the need for sensors and communication networks for a correct operation. In Section 3, a study of Wireless Sensor and Actuator Networks as an interesting option to achieve a Smart Electrical Grid, from generation to end customers including MGs, is carried out. Section 4 reviews different communication protocols and analyzes their potential application to WSANs, in the context of SG management. The perspectives and main challenges of the future intelligent grid, concerning the operation of MGs as well as the interoperability and convergence issues towards a multi-generation scenario, are presented in Section 5. Finally, Section 6 concludes this paper.

2. Principles of Electrical Microgrid Management

Taking into account the particular nature of an electrical MG, which combines electrical characteristics with devices needing more or less intelligence, the appropriate applicable management procedures must cover not only the energy balance into the MG, but also the correct operation of their different intelligent devices. Figure 2 depicts the basic architecture of a MG with a hierarchical centralized management system [5].

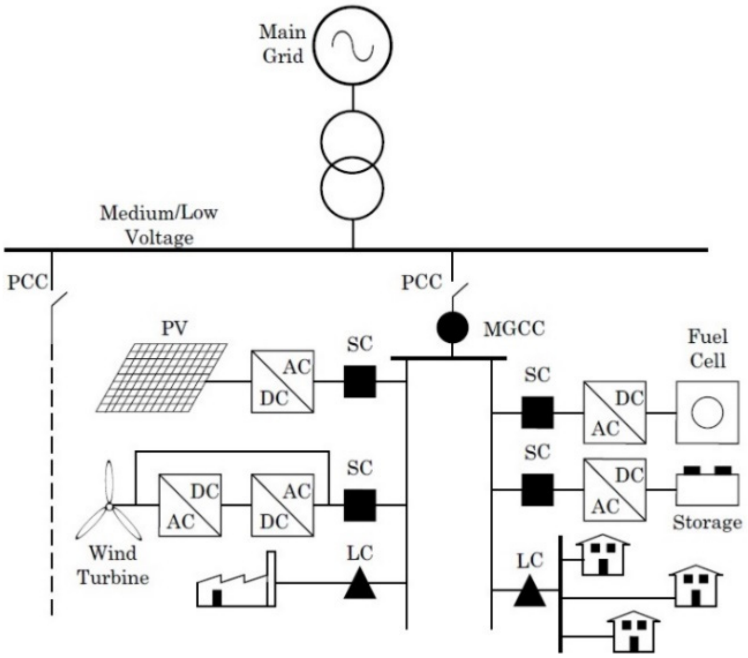

Figure 2. Basic structure of a microgrid (MG), including a centralized management system.

The Microgrid Central Controller (MGCC) is the main component of the architecture, responsible for different high-level management tasks. In a secondary level are placed the Source Controllers (SCs) and the Load Controllers (LCs). The Point of Common Coupling (PCC) is the connection between the MG and the main grid, physically based on a static switch. The MG will operate in grid-connected or islanded mode according to the state of the switch; that is, closed or opened.

2.1. Hierarchical Management

Microgrids need management mechanisms in order to ensure the correct operation and coordination of the different controllers, which must supervise several issues such as the power quality, the load sharing between electrical sources, or the connection and disconnection to the main grid. Traditionally, this control has been achieved by means of a three-level hierarchical sche [6].

- Grid level: This is the outer level of the hierarchical management architecture. The main elements are the distribution network operator (DNO) and the market operator (MO). Their main roles are, respectively, to communicate with different microgrid central controllers (MGCCs), and to manage the MG when it operates on the market (connected to the grid).
- Management level: This stage is controlled by the MGCC, which ensures the synchronization between the MG and the main grid or the quality of the voltage and frequency of the MG, among other functions.

- Field level: The inner level of the management scheme is devoted to control the MG at the loads and sources level (balance between generation and consumption, islanding detection, power balance, *etc.*).

This three-level hierarchical scheme is usually implemented in a centralized manner, composed of primary, secondary and tertiary control loops [7–9], as shown in Figure 3.

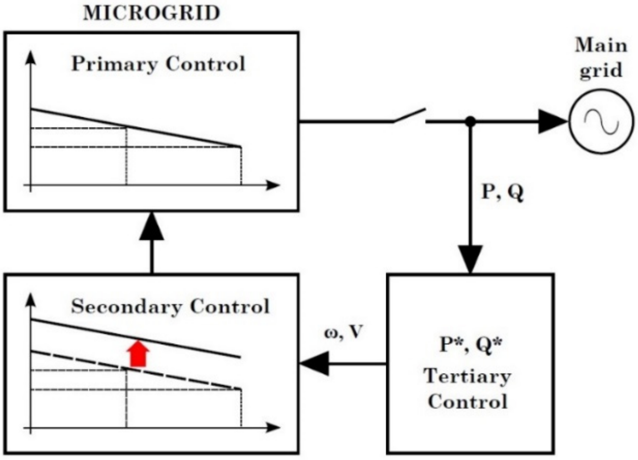

Figure 3. Primary, secondary and tertiary control loops.

Primary regulation is based on the "Voltage *vs.* Reactive Power droop control" and "Frequency *vs.* Real Power droop control". These two techniques, largely employed in high power electrical grids, can be also utilized in MGs in grid connected mode and in islanding [10]. The secondary control is necessary in order to restore the voltage frequency and amplitude, values that have been modified by the techniques applied during the primary control. The tertiary control is employed during the grid connected operation of the MG to control the real and reactive power exchange between the main grid and the MG (and *vice-versa*). It is also possible to apply economic criteria to fix the power levels to be exchanged.

It must be noted that the tertiary control only acts when the MG is connected to the main grid. Secondary control can acts in grid connected mode or in islanding. Secondary control must be centralized, even if the primary control is applied in a decentralized way. The reason is that all the MG power converters must reach the same values in order to correctly restore the system. Thus, to achieve this centralized mode of operation, the application of sensors and actuators that exchange the needed data (measurements and commands) by means of a communication network, is an interesting solution.

2.2. Centralized vs. Decentralized Management

The three-level hierarchical centralized management presented previously can be also implemented employing a decentralized architecture [11], mainly by means of the multi-agent system (MAS) based control [12–14]. This approach proposes the installation of an "agent" in each controller of the MG. On the other hand, centralized management of MGs are interesting from the point of view of simplicity of operation and decision making, which is easier using a central controller.

Nevertheless, in order to palliate the drawbacks of centralized control, intermediate solutions that combine the simplicity of centralized control with the advantages of decentralized methods can also be applied. In this framework, the employ of wireless communication protocols [15] can be an interesting solution that shows the importance of the application of communication protocols to manage MGs in the context of an intelligent electrical grid.

2.3. Demand Side Management

Traditionally, the balance between energy generation and consumption in electrical grids has been accomplished applying Supply Side Management (SSM) techniques. Basically, SSM is based on the increase of the power generation in energy plants during the demand peak hours. Nevertheless, for sudden small variations in the energy demand, SSM is not effective because of the long time needed for energy plants to activate their electrical generators. Therefore, another possibility is to apply a Demand Side Management (DSM) strategy, a concept known and proposed for many years. There are different but near visions in the scientific community concerning the DSM procedures. For several authors [16], DSM can be categorized, according to the timing and the impact over the customer, into: Energy Efficiency, Time of Use, Demand Response (DR) and Spinning Reserve. Other authors make the distinction between DSM (energy audits, improvements of the operation and maintenance, replacement or retrofit, load-shaping strategies, and installation of control devices), DR and Distributed Energy Resources programs [17].

Nowadays, in the frame of SGs, new techniques have been proposed [18–20]. In general, these solutions are based on economic incentives and intelligent management of generation and storage systems. Once again, the role of intelligent counters based on WSANs and communication techniques is crucial in order to achieve a correct DSM mechanism.

3. Management of Electrical Grids by Means of WSANs

The transformation suffered by the classical electrical network due to the installation of MGs (mainly the application of active management techniques at the distribution network level) allows the application of new technologies in terms of sensors and actuators, and the wireless communication protocols to transmit the measured data and the messages containing the control instructions. This section introduces first the main characteristics of a Wireless Sensor and Actuator Network, to survey afterwards the potential of WSANs for the intelligent management of electrical grids, from the power generation systems to the end user, passing through energy transmission and distribution networks where MGs are usually placed.

3.1. Main Characteristics of a WSAN

The development since last years of smart sensors, thanks to the spread of Micro Electro Mechanical Systems (MEMS), has contributed in a major way to the recent expansion of Wireless Sensor and Actuator Networks. WSANs are normally composed of a large number of nodes, which are low power devices generally equipped with one or more sensing units (composed of sensors and, eventually, analog to digital converters), an actuator, a processing unit that includes a limited memory, a radio transceiver, and the power supply. Figure 4 shows the basic architecture of a typical node of a WSAN.

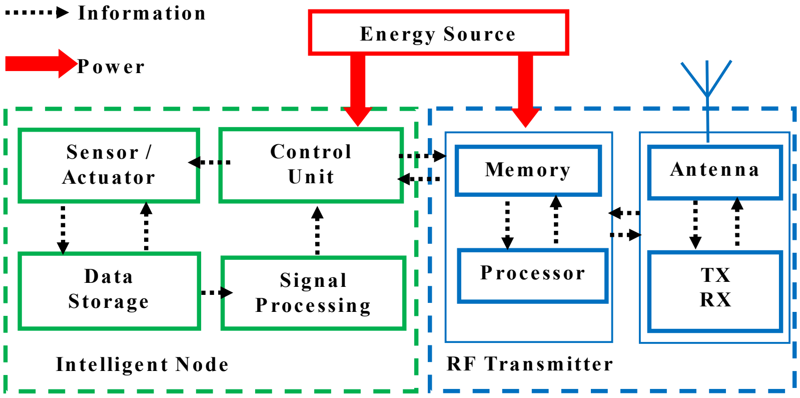

Figure 4. Basic architecture of a WSAN node.

Taking into account the special characteristics of the operating scenarios of WSANs, the most important design factors are listed below [21].

- Hardware constraints: The size of nodes, as well as their weight, must be as small as possible.
- Power consumption: This is one of the main constraints for a sensor/actuator node. Batteries are the principal power source for nodes, along with (but not necessarily) energy harvesting solutions. Therefore, the power consumption must be dramatically minimized.
- Fault tolerance: The correct operation of a WSAN must not be disturbed by the failure of one or more sensors.
- Scalability: It is necessary to develop management techniques to deal with networks containing up to hundreds or thousands of nodes (each node supporting a sensor and/or an actuator). The scalability is directly linked with the network topology.
- Transmission media: Communication among nodes is implemented by means of wireless technologies, and messages are broadcasted directly to the medium. Thus, security and privacy mechanisms must be implemented.
- Operation environment: Sensor/actuator nodes must be able to work in harsh environments, in terms of extreme temperatures, high humidity levels, electromagnetic interferences, vibrations, *etc*.

The main characteristics of WSANs are exhaustively surveyed in [22], including the types of sensor networks, applications, operative systems, standards, network services or communication protocols. On the other hand, the most relevant experimental WSANs deployed over the World are reviewed in [23]. These test platforms are decisive to enhance the performances of WSANs from several points of view: nodes technology, communication protocols or energy saving, among others.

To conclude, it is important to highlight the application of WSANs to manage different issues of the electrical grid at different levels, in the frame of a Smart Grid scenario [24–26]. The next sections will deal more in detail with the use of WSANs to achieve intelligent electrical grids.

3.2. Application of WSANs to Manage the Whole Electrical Grid

WSANs offer significant advantages compared to traditional wired monitoring solutions and, more precisely, in the context of electrical grids that include MGs at the distribution network level, and SGs [27]. Nowadays, typical wired sensors present high cost and low flexibility compared with wireless solutions. In addition to their low-cost and easiness of deployment, WSANs are adapted to the management of electrical grids because they can be deployed over a large area, covering the different feeders and buses of the network. In addition, the embedded intelligence of the nodes allows implementing fault tolerant control algorithms [28]. These capabilities make WSANs a promising solution to gather operation information not only from the distributed energy production units, but also from the different equipment, including those placed at the consumer sites. The collected data allow the network operator to rapidly establish the necessary mechanisms to face different critical events, such as sudden variations in power generation or equipment failures, in an autonomous and appropriate way [29].

3.2.1. WSANs for Power Generation Management

In the conventional electrical grid, wired sensor technologies are largely used in power plants to monitor critical parameters of power generators, such as current, voltage or temperature. Because of their onerous installation and maintenance costs, these sensors are not suitable to supervise the increasing number of renewable energy generation installations, such as solar or wind farms. Nevertheless, the penetration of renewable energies in the future electrical grid and, more particularly in MGs, mainly depends on the capacity of the grid to monitor this number of generation facilities that often operate in remote areas and in harsh environments. Therefore, due to the variability of renewable energy production, it is necessary to implement real time data collection platforms in order to predict, as far as possible, the potential generation level. The collected data can be thus employed not only to minimize the impact caused by the intermittent generation, but also to optimize the energy storage when the generation is higher than the energy consumption.

In this context, WSANs play a key role in order to remotely monitor, via wireless communication networks, renewable power generation systems at low cost and offering a flexible and simple deployment [30]. Hence, WSANs could be used to collect ambient data such as wind speed and solar irradiance in order to optimize wind or photovoltaic generation applying different predictive algorithms [31,32]. Another interesting application of WSANs is the early detection and correction of eventual failures of the generation units. As addressed in [33], wireless accelerometers are used to measure the vibrations of wind turbine blades with the goal to anticipate the maintenance tasks. If the mechanical stress suffered by the blades is excessive, the actuators can modify their orientation or, in the worst case, stop the wind turbine. The data collected by the sensors can also be utilized to detect the disconnection of a MG from the main grid, and to ensure the balance between produced and consumed energy, in grid connected mode or in islanding [34]. Finally, some research works, as in [35], have discussed the possibility of using WSANs instead of conventional wired sensor solutions in industrial power plants to predict and evaluate the energy production.

3.2.2. WSANs for Energy Transmission and Distribution Networks Management

Transmission and distribution electrical networks are responsible of energy transportation from the power generation sites to the end users, and they are mainly composed of overhead and underground power lines, transmission towers, transformers and substations. Traditionally, the energy transmission has been performed in alternative current (AC). Nevertheless, the interest on transmission in direct current (DC), also in a SG scenario [36], is increasing from several years due to some advantages compared to AC transmission [37], such us the lower number of needed cables, the lower resistivity of a conductor in DC, or the lack of reactive power, among others. Nevertheless, in both cases, any breakdown or failure in the equipment will result in a blackout for the end users. Consequently, the reliability must be assured, including supervision methods that will increase the robustness and the fault tolerance of this segment of the electrical grid.

In this frame, WSANs can provide promising monitoring tools adapted to the large size of distribution networks. As mentioned in the literature [38,39], low cost and flexible solutions are applied at the transmission and distribution level for overhead line and underground cable monitoring, power quality measurements, substation management and control, fault detection, cable thermal and vibration monitoring. The analysis of the data collected by sensors allows detecting and isolating (with the correct actuators, such as remotely controlled circuit breakers) failures or power disturbances in the grid, avoiding any cascading effect over the whole electrical network.

Hierarchical and hybrid communication structures have also been proposed to enlarge the fault detection and diagnosis effectiveness of WSANs along the vast geographical area covered by the transmission and distribution lines. In [40], a two-level hierarchical communication system is employed to increase the scalability of a WSAN that is used for the detection of mechanical failures in transmission systems. A three-level hierarchical wireless data communication approach is proposed in [41]. This solution, dedicated to large-scale deployment of WSANs in electrical transmission and distribution grids, uses the hybridization of ZigBee, cellular networks and optical fiber to guarantee the required robustness of the transmission system.

3.2.3. WSANs Applied to End Users Management

In a SG scenario, power grid operators need tools capable of communicating with the energy consumers in order to collect online information concerning their energy consumption behavior [42]. These tools can also be used to remotely control the energy production of distributed generation systems, such as solar panels or wind turbines, placed at the customer sites. All these collected data, issued from the direct communication link with the end user, are needed to enhance the reliability of the electrical grid and to better manage its energy balance by means of different procedures applied at the customer side and, more precisely, DR.

In general, the main customer side applications that can be cited are Wireless Automatic Meter Reading (WAMR), Advanced Metering Infrastructure (AMI), residential energy management, distributed generation management, building automation, demand-side load management, process control monitoring, and equipment management and monitoring.

A number of new applications that employ WSANs, such as smart meters [43–45] or AMI [46–48], are proposed to establish a link between the network operator and the end users. WAMR [49], which is a typical SG application, offers the ability to remotely monitor the customer energy consumption in order to prevent power disturbances during peak hours, using customer appliances advanced control and load shedding. As mentioned in [50], low-cost and low-power WSANs that use in example ZigBee or Machine-to-Machine (M2M) communications are the most suitable technology for WAMR systems. Moreover, customers are able to access the information issued from these WSANs through web services [51], allowing not only the analysis of their energy generation or consumption (with the aim of helping end users to optimize their consumption habits), but also to remotely control different appliances. Optimization-based Residential Energy Management (OREM) and in-Home Energy Management (iHEM) are also proposed for residential demand management [52]. These solutions, whose aim is to minimize the end-user energy consumption, utilize a central Energy Management Unit (EMU), WSANs and smart appliances.

Finally, it is important to highlight the increasing number of renewable generation and MGs installed at the end users sites. Thus, the implementation of WSANs to monitor and control customer wind turbines or solar panels, along with energy storage solutions, seems to be necessary in order to increase the reliability of these distributed generation systems [53]. Once again, wireless sensors and controllers using specific communication protocols can be used at MG level to monitor and to connect or disconnect distributed sources or electric loads in order to improve DSM, by adapting the energy production to the customer consumption. In addition, this type of WSANs could also be used for islanding detection, and their main challenge is to provide to the MG the capability to maintain their efficiency after islanding.

3.3. Synthesis

To conclude, Table 1 gives an overview of potential WSAN applications suitable for SG and MG management, in terms of data rate, latency and reliability.

Table 1. Potential WSAN applications for SG and MG management.

Electrical Grid Segment	Application	Data Rate	Latency	Reliability
Generation	Traditional power plant monitoring	High	Low	High
	Wind or solar farm monitoring	Medium	Low	High
Transmission and distribution	Line or cable monitoring and fault detection	Low	Low	Very High
	Distribution substation	Low	Low	Very High
	Outage detection	Low	Low	Very High
Customer-side	WAMR	Low	High	Medium
	iHEM/OREM	Low	Medium	Medium
	Distributed generation monitoring and control	Low	Medium	Medium

As has been seen, WSANs are a key element in the evolution of the traditional electrical grid to a SG, from the energy generation units to the end customer, passing through the transport and distribution lines. Low-cost, easiness of deployment, fault-tolerance and high flexibility are the main characteristics that make WSANs solutions suitable for SG monitoring and control. Nevertheless, the efficiency and reliability of WSANs to be optimally applied to the SGs mainly depend on communication performances such as Bit Error Rate (BER), latency and security in harsh environments.

The importance of communication protocols on the performance of WSANs in a SG scenario that includes MGs will be analyzed in the next sections.

4. Communication Technologies for WSANs Applied to the SG

Communication network technologies constitute a solution to support data transmission between consumer appliances, different equipment of the electrical grid and the data center of the SG. Using these technologies, SGs improve their capability to communicate with the customers to remotely monitor electrical equipment, to detect their failures and limitations, to remotely control them in order to prevent power disturbances and to manage more efficiently the overall electrical grid [54,55]. This section overviews the origins of the communication networks applied to monitor electrical grids, to further survey the communication protocols suitable for WSANs applied to a MG and SG scenario.

4.1. The Origins of Communication Technologies in Electrical Grids

The interest on the application of communication technologies in order to help the management tasks of electrical grids begins with the expansion of the electrical network and the increase of the number of connections and branched devices. The first objective at the beginning was to ensure the correct operation of the grid and to rapidly face possible disturbances and breakdowns [56]. In the 1950s analog communications were usually employed to measure the energy generation of power plants and the total consumption, as well as to control the frequency and the voltage of the grid. The development of digital computers from 1960 allowed the creation of Remote Terminal Units (RTUs), employed to obtain in real time the values of real and reactive powers as well as the state of the transmission electrical substations. The acquired values were sent to a central computer known as Master Terminal Unit (MTU), through dedicated communication channels: the Supervisory Control And Data Acquisition (SCADA) system was born [57,58].

The SCADA system was the best solution to be applied in the first electrical grids, whose structure was centralized. However, the energy market liberalization in the 1990s caused a decentralization of the grid and, therefore, the need for a revision of control methods. Nowadays, new communication technologies based on the Internet or on Common Information Model (CIM) are integrated in the traditional SCADA system, as can be seen in Figure 5.

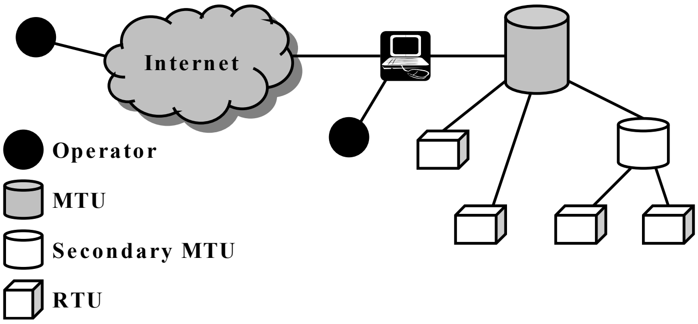

Figure 5. Architecture of a modern Supervisory Control And Data Acquisition (SCADA) system, connected to Internet.

Moreover, the generalization of renewable sources, as well as the distributed generation and MGs expansion, is inducing a transformation of the distribution electrical grid [59,60] that must evolve from a passive to an active role from the point of view of automation and management [61,62]. The application of advanced management systems in electrical grids is the basis to transform them into Smart Grids. Some authors define as the "Third Industrial Revolution" the transformation of conventional electrical grids into SGs that include a large volume of renewable and distributed generation, managed by means of control systems based on communication protocols [63].

This last aspect is essential because it reveals the need of a suitable communication network in order to monitor and transmit measured data from different parts of the electrical grid, allowing the detection of any operation problem and assuring a correct management of SGs and MGs [64]. The combination of communication techniques to collect and transmit measured data, and the grid management performed by means of those data is the basis of Automatic Meter Reading (AMR) systems [65]. Some interesting applications of AMR are the DR (real time pricing) [66,67], fault and islanding detection [68], system protection, fraud detection and remote telemetry, among others. In this context, electrical MGs, due to the intelligent control and communication solutions that must be applied in order to monitor and manage their correct operation, can be considered a promising starting point to transform the conventional grid into a SG.

4.2. From Home Area Network to Wide Area Network

As it has been pointed out previously in this paper, SGs present a decentralized infrastructure (contrary to classical power grids) that allows the delivery of energy from generation units to the consumers and the integration of renewable energy sources. In this frame, WSANs are a suitable solution that can be deployed over the whole grid (power generation, power delivery and power consumers), to guaranty its reliability in an intelligent way. However, communication technologies are imperative to the correct operation of a WSAN, assuring the transmission of the data measured by sensors and the commands to the actuators [69,70].

The objective now is to study the different communication protocols that can be employed in a WSAN that operates in a SG scenario, including MGs whose operation must be managed. As the first step of this analysis, a SG can be generally subdivided in three network levels, as it is shown in Figure 6.

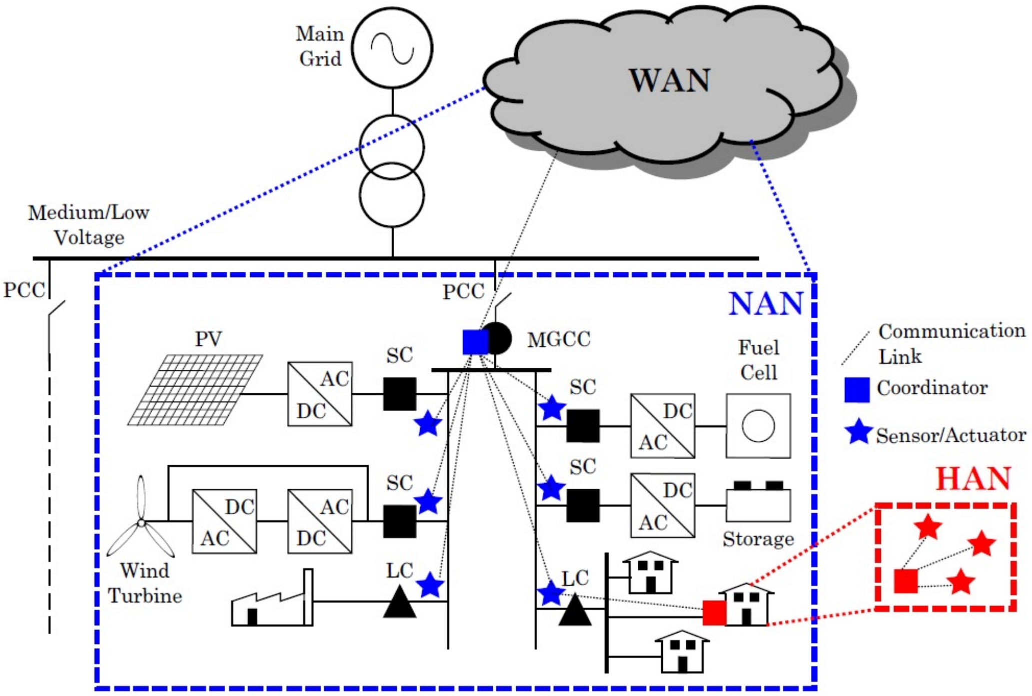

Figure 6. The three different communication network levels of a SG.

The main characteristics of each level will delimit the candidate communication protocols:

- Home Area Network (HAN), dedicated to connect different kinds of devices in the home such as displays, computers and electricity or gas meters. Home automation applications are also placed at the HAN level. In the context of SGs, HANs represent the lowest level of the overall infrastructure and permit, for example, to connect smart meters and control devices for distributed renewable sources and Plug-in Hybrid Electric Vehicles, and to implement DR applications. The coverage range of a HAN is usually limited to ten meters.

- Neighborhood Area Network (NAN), which plays the role of gateway between HANs and the upper level. Very frequently, NANs transmit the data information between customer locations, issued from different HANs, and data aggregation points. Therefore, NAN must guarantee a range of around thousands of meters. Besides, the coverage of a NAN is particularly well adapted to the dimensions of medium-size electrical MGs; that is, a MG comprising some buildings (techno poles, residential areas or little villages) or installed in large buildings such as hospitals.
- Wide Area Network (WAN), which constitutes the backbone of SG communication network. The main task of a WAN is to transfer the overall collected data to grid operators, and command messages to the consumers. Thus, WAN must be able to carry large amount of data on wide range. Nowadays, the Internet is the most important WAN, allowing the transmission of high data volumes worldwide.

Taking into account these three network levels, the next sections will describe the generalities of different communication protocols that can be potentially employed to support the communication needs at each stage.

4.2.1. Home Area Networks and Neighborhood Area Networks

As defined previously, HANs and NANs constitute the two lowest levels of the SG network. Considering Figure 6, these levels cover the MG area and play a key role in DSM applications and home automation [71]. Moreover, they are particularly adapted to the deployment of low cost wireless communication solutions and WSANs. Consequently, the communication protocols employed at HAN and NAN levels must fulfill the MG and DSM application needs, mainly low coverage range, small amount of information to be transmitted, limited number of nodes, and maximal battery lifetime of the wireless sensors and actuators. The main candidate wireless communication technologies for HAN and NAN levels include the following.

- Bluetooth: This low power consumption wireless communication protocol, whose physical layer is defined by the IEEE 802.15.1 standard, was designed to be applied in personal area networks (PANs). Bluetooth has a short-range coverage of 10 m that can be enlarged to 100 m by means of repeaters, offering a data rate of about 720 kbps. In HANs, Bluetooth and their low-energy version (Bluetooth LE [72,73]) are interesting solutions to interface smart meters and customer devices.
- ZigBee: Based on the IEEE 802.15.4 standard and adapted to mesh networking and low duty-cycle applications, ZigBee proposes a data rate of 250 kbps for a coverage range of 100 m without repeaters. It is able to transmit data employing different ISM frequency bands such as 868 MHz, 915 MHz and 2.4 GHz. Nowadays, ZigBee is considered one of the most suitable technologies for networking devices in HANs. Consequently, it is frequently used as communication protocol for WSANs applications, such as consumer appliances control, distribution system monitoring or smart power monitoring.
- Wireless Fidelity (WiFi): Nowadays, WiFi is the wireless technology most commonly deployed in homes and buildings, and their characteristics make WiFi an attractive communication protocol for NANs. Based on the IEEE 802.11 standard, this low cost solution offers a high data rate, up to few Gbps, along with a coverage range of about 200 m. However, the high power consumption is the main drawback for WiFi to be used as communication protocol in WSANs.
- Other solutions that can be applied at HAN and NAN levels are the ultra-low-power emerging wireless communication technologies adapted to M2M applications and particularly, to WSANs [74]. These wireless technologies, proposed for instance by Wavenis, LoRa or SIGFOX, present a long-range coverage, from 200 m to few tens of kilometers, with low data rates (up to 100 kbps) [75].

Finally, it is always possible to adapt the existent protocols to a particular WSAN that operates in a well-defined scenario, in order to optimize the communication performances, maximizing at the same time the battery life of the sensor and actuator nodes. In this way, Medium Access Control (MAC) protocols have evolved in order to match the needs of WSANs [76], and new specific routing algorithms have also been proposed to reduce the energy consumption [77].

4.2.2. Wide Area Network

As has been explained before, WAN is the most important element of SG because it is used to centralize all the aggregated data issued from the overall electrical grids on a remote data center. Moreover, WAN could be used to diffuse control information from this data center to consumer appliances or to power plants in order to improve the efficiency of energy distribution. Therefore, WAN technologies must ensure the capacity to transport a very large amount of data with a range of several kilometers and high data rates.

On the other hand, the sensor and actuators that compose a WSAN are not well adapted to the communication needs of a WAN in terms of data rate or energy autonomy. Nevertheless, the data measured by sensors can be transmitted to a "central node" which could be interfaced with a WAN such as the Internet. This central node will concentrate the intelligence of the whole WSAN, and it will not be constrained in terms of energy autonomy.

Therefore, it is necessary to overview the main communication protocols that can be applied to WANs, because WSANs may be interfaced with them in a SG scenario. The main candidate communication technologies for the WAN level of a SG include the following.

- Ethernet, which guarantees high data rates, up to 100 Gbps, ensures the data transport up to 10 kilometers using optical fiber without repeaters.
- Wireless Broadband Power Line is a hybrid technology between BPL and wireless techniques [78,79]. The operating principle consists of sending the communication signal through the medium voltage electrical lines, reaching a data rate up to 200 Gbps over 1 to 3 km.
- WiMAX: Based on IEEE 802.16 standard, Worldwide Interoperability Microwave Access ensures a high data rate access, between 11 Mbps and 108 Mbps, to the Internet network with a coverage distance of several kilometers.
- Cellular technologies: Technologies currently used for mobile phone communications could also be another possibility to manage intelligent electrical grids by means of their capability of data transmission. In this case, Global System for Mobile Communication (GSM) offers the lowest data rate, around 9.6 kbps, whereas the higher data rate transmissions are reached by Universal Mobile Telecommunication System (UMTS) and High-Speed Downlink Packet Access (HSDPA), which offers 2 Mbps and 14 Mbps, respectively [80,81]. These solutions, which are widespread over the world, also provide wide range coverage, up to few kilometers. The 4th generation (4G), based on LTE, reaches data rates up to 100 Mbps [82,83].
- IEEE 802.22: Due to the lack of frequency resources, this standard constitutes an alternative solution to ensure long-range wireless communication by using white spaces in the overall frequency spectrum such as television band (TVWS). This solution offers a range of 10 to 100 km and data rates of few Mbps, needs the cognitive radio (CR) [84] technology in order to detect unused frequency and to transmit data.

4.3. Synthesis

The study performed in this section reveals that candidate communication technologies for SG management have different characteristics in terms of data rate, range and power consumption, which will impact their employ in WSANs. Therefore, there is a need for interoperability between these technologies in order to fulfill the overall requirements of a SG, from HAN to WAN, such as bi-directional coordination, data gathering and information processing, real-time and online processing, or proactiveness. Figure 7 lists the proposed communication technologies, for each level of the SG.

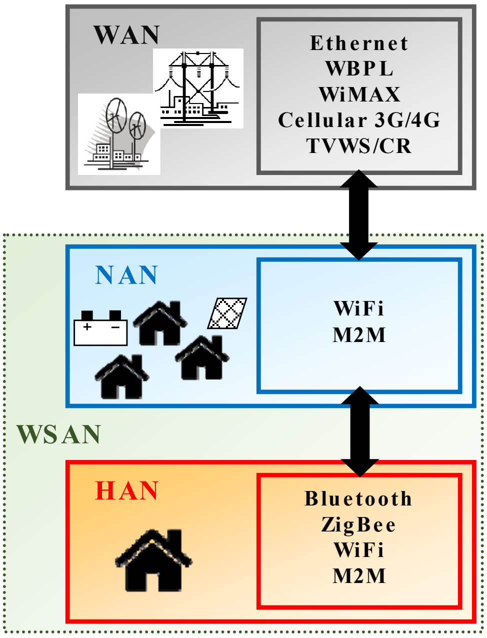

Figure 7. The proposed communication technologies for each level of the SG.

Table 2 profiles the most interesting characteristics, from the point of view of their application to grid management using WSANs, of the presented communication protocols.

Table 2. Comparison of the main characteristics of the Home Area Network (HAN) and Neighborhood Area Network (NAN) communication solutions.

SG Network Level	Technology	Frequency Band	Data Rate	Range	Power Consumption
HAN	Bluetooth	2.4 GHz	720 kbps	10 m	Classical: ≈100 mW Low-energy: ≈10 mW
	ZigBee	868 MHz/915 MHz 2.4 GHz	250 kbps	100 m	≈10 mW
HAN and NAN	WiFi	2.4 GHz	Up to few Gbps	200 m	≈1.5 W
	M2M solutions	ISM band	Up to 100 kbps	From 200 m to tens of km	≈50 mW

5. The Evolution towards a Global Smart Grid Deployment: Challenges and Perspectives

The aim of this section is to overview the main concerns related to the evolution of the electrical grid to a Smart Grid. Several aspects will be commented, starting with data communication and the problems due to the application of WSANs, to finish with the perspective of a multi-generation SG, scenario where intelligent electrical MGs are called to play a significant role to ensure the interoperability and convergence of different technologies.

5.1. Data Communication and WSANs

Electrical grids present particular characteristics mainly in terms of infrastructure, equipment and electromagnetic interferences. The implantation of electrical MGs has a major impact over the classical network topology and power generation. Even more, the evolution towards a SG implies new issues in terms of communication and security, and WSANs are also constrained by power energy, in example.

The combination of all these factors implies new solutions to be found to ensure the adequate reliability concerning the communication and the WSANs nodes operation.

5.1.1. Harsh Environmental Operation Scenario

Electrical grids constitute a hostile environment for any installation of communication technologies, especially when the transmission is realized without wires. The electromagnetic pollution generated by high currents and voltages, as well as high power commutation devices (present in DC-DC converters and inverters) are sources of problems for the correct operation of WSANs: sensors and actuators will be impacted not only from the point of view of radiofrequency interferences, but also in terms of high humidity levels, dust, caustic or corrosive ambiances and vibrations. Concerning the network communication topology, the varying channel characteristics and eventual node failures can modify the network topology, disturbing the information exchange between sensors. The reliability of the communication network is also perturbed in terms on latency and packet errors. In MGs, the impact caused by islanding must be also considered, in terms of network topology variation and electrical disturbances that will be generated.

Therefore, it is crucial to assure the robustness of WSANs in order to achieve a correct operation and communication between nodes. Traditionally, wired communications such as Power Line Carrier (PLC) have been employed to transmit information through the electrical grid [85]. Nevertheless, PLC is also affected by the power lines characteristics [86,87]. Thus, wireless communication protocols can be utilized, assuring their immunity face to disturbances. A possibility is to implement fault diagnosis methods to detect failures that can occur in any component of the node (sensor, actuator, transceiver, memory, or power system) [88].

5.1.2. Quality of Service

Assuring the system reliability is a crucial issue in power grids. However, the evolution from a classical grid to a SG involves a number of new technologies to be applied that may affect the Quality of Service (QoS) of the system. Taking into account the different applications envisaged for the SGs, several levels of QoS will be required, in terms of reliability, latency and throughput [89]. In this context, the deployment of faster and more robust control devices and embedded intelligent systems (IEDs) in the grid, in parallel with secured communication and information technologies and protocols, will have an important role in order to increase the system robustness. Concerning the impact of the chosen communication protocol, wired technologies offer a good level of reliability and security, but they are in general costly. On the other hand, wireless technologies with a certain level of security constitute an interesting choice because of the reduced installation costs, in spite of their lower robustness level.

5.1.3. Security

The application of conventional communication protocols for the management of electrical grids implies a major revision of the existent protection and confidentiality mechanisms for the transmitted data [90,91]. Moreover, the use of Internet as information transmission support in the SG is the source of new vulnerabilities for the WSANs that make part of it, such as intrusions and denial of service (DoS) attacks [92,93]. It is then necessary to apply security mechanisms that must assure at least three main aspects:

- Privacy, a critical issue that is very frequently attacked. Privacy must be assured not only for related customer information, but also for the commercial transactions related with the operation of the whole electrical grid. Some privacy protection mechanisms are based on standard schemes. In example, EG2 (one recommendation proposed by the Expert Groups of the European Commission) recommends a technique that separates the smart metering data into low-frequency attributable data (data used for billing) and high-frequency anonymous technical data (data used for demand side management) [69].

- Integrity, whose aim is to avoid illegal modifications of the transmitted data. Authentication mechanisms [94] are traditional solutions in order to ensure a correct identification of the transmitter and the receiver of the message, allowing the detection of possible data corruption.
- Availability, that is, the possibility for authorized users to get access to the network services even if an attack has occurred. Communication among nodes and a central access control system can be an appropriate solution in order to ensure the availability of the network.

Another interesting security aspect is secrecy; that is, the prevention of passive attacks and unauthorized access to confidential and sensitive customer data, such as the billing or the smart meter information. All these requirements must be combined with early detection methods, in order to eliminate false alarms caused by undesirable communication delays, and to discover any unauthorized manipulation of transmitted information. Security in SG communications can be also increased implementing public key infrastructures (PKIs) and trusted computing methodologies [95]. Concerning the WSANs, some basic requirements for achieving a good level of security are prohibition of unauthorized nodes to access to the network information, implementation of distribution key mechanisms robust enough, and encryption of public information [96]. The security level can also be increased by means of secure routing protocols or secure data aggregation procedures [97].

5.1.4. Resource Constraints

Finally, it is interesting to point to another challenge concerning the application of WSANs to grid management: the limited resources of sensor nodes, which are constrained by energy availability, memory size and processing capacity. The most important resource is the battery energy supply, which is in general limited [98]. Thus, taking into account that periodic replacements of node batteries is an unaffordable task, a WSAN must be designed to maximize its autonomy, including adapted operative systems [99,100] or communication strategies, such as optimized routing techniques [101]. The battery life of nodes can be also increased by applying topology control algorithms [102]. Energy harvesting solutions are other possibilities to increase the energetic autonomy of the sensors [103]. Some of the candidate technologies for harvesting energy applicable to sensor nodes are solar and thermal, vibration-based, and electromagnetic wave and radiofrequency [104].

5.2. Evolution and Adaptability of MGs towards a SG Scenario

SG makes reference not only to the application of new management, measurement or communication technologies to the electrical grid. Indeed, a new paradigm of electrical grid in terms of new connected equipment or new generation possibilities must be imagined. Once again, MGs can be seen as one of the key elements to accomplish this necessary transformation of the grid.

5.2.1. New End Users and Equipment Connected to the Grid

A rapid evolution of the number of actors implied in the power grid is expected, mainly smart devices and electric/hybrid vehicles. In the near future, plenty of smart devices will be part of the power grid, connected through communication networks: smart meters, smart sensor nodes, smart data collectors, renewable energy sources. As a consequence, it will be necessary to implement scalable communication architectures to deal with the large quantity of data generated by those devices [105]. One of the proposed solutions is to use a Meter Data Management System (MDMS) which stores and processes data received thru the Data Aggregator Units (DAUs). Each DAU collects measurement data from the nearness smart meters and acts as a temporary buffer. The Smart Grid should be able to propose reliable protocols with advanced issues as self-configuration possibility and reinforced security.

The number of electric and Plug-in Hybrid Electric Vehicles (PHEV) is expected to rise with the aim of progressively decreasing the fossil fuel consumption. In the absence of an adapted control strategy, the simultaneous charging of an important number of vehicles during the peak consumption periods can affect the grid operation [106]. Fortunately, those vehicles can have an important place to take in the management of the Smart Grids by their own storage capacity. Batteries can be charged during the off-peak hours and can supply energy to the grid during peak hours [107,108]. The load scheduling can be envisaged by means of attractive electricity prices and allowing users to decide the quantity of energy to buy or to sell. By their intrinsic storage capability, electric vehicles can provide additional services to the grid such as participation on the voltage and frequency regulation, peak power diminution and reactive power injection or absorption, thereby increasing the grid efficiency and stability, and reducing at the same time the power system operating cost [109].

5.2.2. Towards a Multi-Generation Scenario

Smart Power Grids constitute a new paradigm of electrical networks not only for the employ of new intelligent management systems, but also for the convergence of different energy sources, with an important role of renewable energies and microgrids. Nevertheless, in the near future, more complex interactions between different generation sources must be considered, as shown in Figure 8.

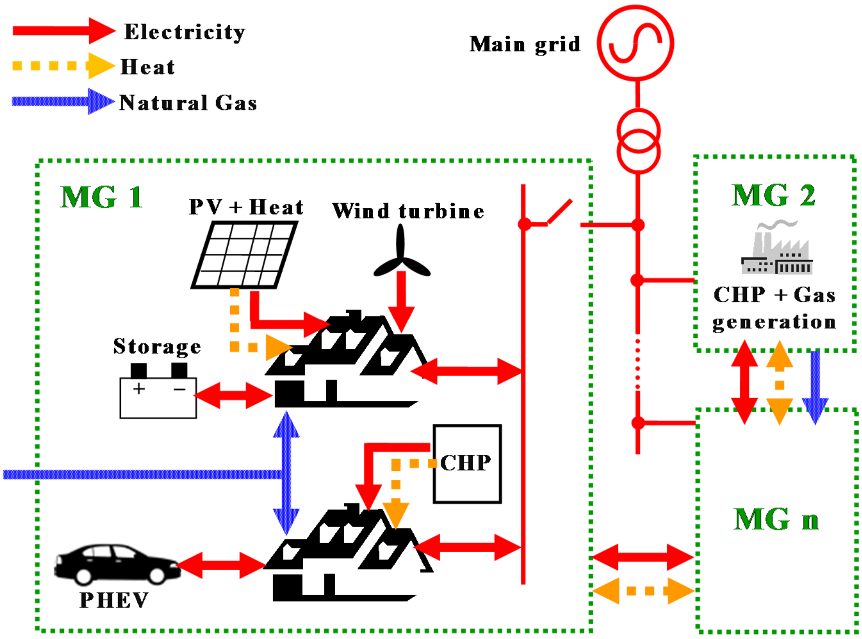

Figure 8. Structure of a "multi-generation" MG scenario.

The Multi Energies Systems (MESs), including the production of electricity, heat, cooling, fuels and even transportation are expected to offer new optimization possibilities [110]. In a MES, storage problems can be cleared up applying all the possible energy conversions. For instance, depending on the scenario, it could be possible to store energy in thermal form (high temperature for heating or low temperature for cooling) combined with classical electrical energy storage. Nowadays, some generation solutions based on interactions between different technologies already exist: combined heat and power (CHP), electric heat pumps (EHP), air conditioning devices, and trigeneration systems (electricity, heat and cooling). CHP is the most studied by the scientific community in various environments: Smart Grids [111], microgrids [112] or smart cities [113,114].

Multi energies experimental test plants have been installed around the world to demonstrate their economic and environmental benefits. One example is the Smart Polygeneration Microgrid of the University of Genoa, composed by CHP units, natural gas boilers, thermal storage, absorbing chiller, a concentrated solar power unit coupled to Stirling engines, electrical storage, photovoltaic panels and recharging stations for electrical vehicles [115]. The optimal daily operation of the system is assured by an operation center that utilizes mathematical models. Other mathematical models are used to optimally design a MES, as the mixed-integer linear programming super-structure model proposed in [116]. The objective is to minimize the overall investment cost and the operating price of the system.

In summary, the real challenge is to make possible the convergence and the complete association of all those energy networks, achieving a correct interoperability. The task is complex considering that the management methods to be applied are quite different. Communication technologies and WSANs will be two of the fundamental points of this future "Super Grid", and the geographical structuration using the microgrid concept can be a solution to limit the quantity of overall data exchange. In this way, a large amount of information will be used only inside the MG for its own management. The SG implementation is based on extraordinary data storage and computation capabilities. In this context, Cloud Computing, thanks to its key characteristics (flexible resources and services shared in network, parallel processing and quasi-omnipresent access), will have an important role to play in the future SG [117].

6. Conclusions

This paper has surveyed the key issues concerning electrical microgrids and Wireless Sensor and Actuator Networks, and its combination in order to transform the classical electrical grid into a Smart Grid. MGs are a new electrical grid paradigm that includes innovative management systems because of their particular characteristics: high renewable energy penetration, presence of energy storage systems, risk of power unbalance, and the most important issue, islanding. In order to assure a correct management of a MG, it is necessary to implement a set of sensors and actuators, which need a communication system to transmit the measured data and the command messages. Thus, Wireless Sensor and Actuator Networks are a promising solution to support the management of a MG, in an intelligent manner. In other words, MGs become more intelligent thanks to the application of WSANs and communication protocols. Even more, MGs can be seen as the first step to offer some level of intelligence to the grid; that is, to achieve a Smart Grid.

A three-level hierarchical centralized management system for MGs has been presented, along with other decentralized solutions. Each model offers some advantages and drawbacks. Centralized systems are simpler to implement than decentralized ones, but they present an architecture that is less resistant when facing potential failures. Consequently, mixed solutions combining the two approaches seem to be a good tradeoff. In any case, a WSAN will be necessary to complete the MG management system.

Moreover, WSANs can be also applied to manage the electrical grid at different levels: power generation, transport and distribution lines and, finally, end users and DSM. However, the needs of each stage are not exactly the same in terms of data rate, latency and reliability. Indeed, the kind of WSAN to be applied may not be the same. In that case, it will be necessary to find solutions to assure the interoperability among the different networks.

Concerning the communication technologies to be used, it is important to identify the network level where the WSAN will be placed. Usually, WSANs are deployed in sites that correspond with HAN or NAN levels. This fact limits the choice of the communication protocol in terms of coverage. On the other hand, the power consumption caused by the protocol must be as low as possible because it will be employed by nodes limited in terms of power supply. There are several protocols that match this important requirement, with ZigBee as the most usually employed. Nevertheless, in some cases, it is necessary to adapt the existent protocols to the real needs of each application.

Finally, some concerns related to the evolution of the grid toward a SG have been presented. It will be necessary to adapt the WSANs physical components to the harsh environment of the electrical grid, and also the security procedures in order to face the new vulnerabilities that will appear. The future SG will be able to integrate plenty of intelligent users and equipment, such as MGs with renewable energy, or PHEV, which will actively participate in the whole management of the network. In addition, the SG will become a multi-generation scenario, more energy-efficient but, at the same time, more difficult to manage. As has been pointed out, assuring the convergence and the correct operation of the different actors that constitute the SG is the real challenge that must be overcome.

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