# Chapter 1
# Introduction to Smart Grid Architecture

**Ersan Kabalci and Yasin Kabalci**

**Abstract** The smart grid that is a new concept introduced at the beginning of the 2000s intends to include bidirectional communication infrastructure to conventional grids in order to enable information and communication technologies (ICTs) at any stage of generation, transmission, distribution, and even consumption sections of utility grids. This chapter introduces essential components and novel technologies of smart grids such as sensor networks, smart metering and monitoring systems, smart management systems, wired and wireless communication technologies, security requirements, and standards and regulations for this concept. First of all, this chapter focuses on the main components of smart grids such as smart sensors and sensor networks, phasor measurement unit (PMU), smart meters (SMs), and wireless sensor networks (WSNs). Then, smart grid applications and main requirements are explained on the basis of advanced metering infrastructure (AMI), demand response (DR), station and substation automation, and demand-side management (DSM). Later, communication systems of smart grid are presented in which the communication systems are classified into two groups as wired and wireless communication systems, and they are comprehensively analyzed. Furthermore, the area networks related to smart grid concept such as home area network (HAN), building area network (BAN), industrial area network (IAN), neighborhood area network (NAN), field area network (FAN), and wide-area network (WAN) are presented in a logical way beginning from generation systems to the user side.

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E. Kabalci (✉)
Department of Electrical and Electronics Engineering, Faculty of Engineering and Architecture,
Nevsehir Haci Bektas Veli University, Zubeyde Hanim Cd. Avanos Yolu, 50300 Nevsehir, Turkey
e-mail: kabalci@nevsehir.edu.tr

Y. Kabalci
Department of Electrical and Electronics Engineering, Faculty of Engineering, Nigde Omer
Halisdemir University, 51240 Nigde, Turkey
e-mail: yasinkabalci@ohu.edu.tr; yasinkabalci@mail.usf.edu

Y. Kabalci
Department of Electrical Engineering, College of Engineering, University of South Florida,
33620 Tampa, FL, USA

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Advanced metering infrastructure · Demand response
Demand-side management · Wireless sensor networks
Power line communication · Smart grid communication networks

## 1.1 Introduction

The conventional power grid has been degraded since its first installation and widespread use all over the world. The fundamental components of legacy power grid are located at generation, transmission, distribution, and consumption sections [1]. The bulk generation includes several conventional and modern power generation systems such as hydrogenerators, combined heat and power (CHP) plants, thermos generators, nuclear power sources. The degraded utility faces with numerous deficiencies distorting the power quality and reliability. The widely known power system deficiencies are caused by voltage instability, intermittency, curtailments, blackouts, and unbalanced or heavy-load situations. The remote monitoring and control systems have been improved and integrated to conventional grid in order to cope with these deficiencies [2].

The global energy demand has been gradually increased since conventional grid installed. The governments and energy suppliers have improved several energy and demand-side management (DSM) programs to meet the demand. The regulations allowing increasing distributed generation (DG) have been put into practice since a few decades ago. In addition to DG programs, use of renewable energy sources (RESs) has also been spread day by day [2]. The researches and developments on physical structure and resource management of conventional grid have put forward another requirement on communication-based systems. This requirement, which has led to improvement of smart grid, was important for source and load management, monitoring the generation, distribution, and consumption rates, and control systems. The smart grid that has been conveyed in the early 2000s is one of the most recent terms implying monitoring and control operations in grid management systems [3, 4]. The smart grid that has been implemented by integrating physical and cyber communication networks to conventional grid improves communication and control features of power network. The essential contribution of smart grid to power network can be summarized as its promotion by enabling two-way power and communication flow [1].

The smart grid infrastructure is implemented to provide a data communication medium in order to carry several signals for measurement, monitoring, management, and control purposes. The smart grid interface is integrated to utility grid at any section including bulk generation, transmission, distribution, and consumption and microgrid installations. The communication interface and medium are required to provide secure, reliable, and efficient transmission. Several research groups have improved the smart grid concept, and a number of whitepapers, reference works, standards, laws, and applications have been introduced. The US Department of Energy has defined smart grid and its characteristic features with a public law in the context of Energy Independence and Security Act of 2007 [5, 6]. The smart grid has been accepted as a goal to be inspired instead of just technological improvement. The law has described various policy sections including modernization of electricity grid, smart grid system, advisory committee and task force for smart grid, research and development on smart grid, interoperability framework, and security attributes of smart grid. The requirement and features of smart grid characterization have been described in the public law as follows [6];

(i) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
(ii) Dynamic optimization of grid operations and resources, with full cyber-security.
(iii) Deployment and integration of distributed resources and generation, including renewable resources.
(iv) Development and incorporation of demand response, demand-side resources, and energy-efficient resources.
(v) Deployment of "smart" technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.
(vi) Integration of "smart" appliances and consumer devices.
(vii) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air-conditioning.
(viii) Provision to consumers of timely information and control options.
(ix) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.
(x) Identification and lowering of unreasonable or unnecessary barriers to adoption of smart grid technologies, practices, and services.

Electric Power Research Institute (EPRI) has brought a new definition to smart grid by developing an initiative named IntelliGrid that has proposed the same name for smart grid description. They defined smart grid as an integration of electrical and information technologies on utility grid. Similarly, several whitepapers and reports made same definitions for smart grid that it is a system based on integrating electrical and communication systems together [7]. A brief and widely accepted definition for smart grid has been proposed by IEEE in IEEE Std 2030–2011 [8] as follows;

"The Smart Grid encompasses the integration of power, communications, and information technologies for an improved electric power infrastructure that serves loads while providing for an ongoing evolution of end-use applications."

The comparisons of conventional and smart grid are listed in Table 1.1 according to the most significant features [9, 10]. The particular features of smart grid have been improved by using enhanced information and communication technologies (ICT) that enabled conventional grid to deliver power in an efficient way. Furthermore, the smart

**Table 1.1** A comparison between conventional and smart grid

| Feature | Conventional grid | Smart grid |
|---|---|---|
| Generation method | Central | Decentralized/DG |
| Monitoring | Manual | Self-monitoring |
| Metering | Electromechanical | Digital |
| Control methods | Limited and passive | Active |
| Transducers | Limited sensors | Unlimited and widespread |
| Communication | One-way | Two-way |
| Power flow | One-way | Two-way |
| Restoration | Manual and local | Self-restoration |
| Grid architecture | Radial | Network |

grid has been enabled to provide transmission of data and information in two-way cyber-secure communication interface. Thus, the computational intelligence has been integrated to the conventional grid, and diagnosing and troubleshoot in grid environment have been performed much more efficiently. The computational intelligence has also been integrated to generation, transmission, distribution, and consumption levels of conventional grid. Hence, the modernized grid has been converted to much more secure, reliable, controllable, and efficient power and data transmission system. The smart grid provides decentralized and DG in generation profile, while the conventional grid has been installed on centralized generation plants. Due to decentralized generation opportunity, the monitoring and measurement systems have been improved to provide self-monitoring features in smart grid. Thus, two-way power and communication features have been achieved in smart grid enhancements. The digitalized metering is another particular contribution of smart grid to conventional grid which is achieved by unlimited and widespread use of smart sensors and sensor networks. The intelligence-based novel grid structure has brought self-restoration and self-healing capabilities, while the conventional grid was being restored manually or locally [9–11].

The IEEE Std 2030–2011 standard supports National Institute of Standards and Technology (NIST) framework coordination and provides several solutions to comprise system-level approach for interoperability. The smart grid, which is defined as system of systems in the standard, has been introduced and handled in terms of interoperability aims. This ability enables any system to communicate with each other by using networks, applications, services, devices, and interfaces with the aid of cyber-physical systems (CPSs). Therefore, any smart grid system is required to incorporate with hardware and software technologies, data transmission solutions, and data exchange networks. The ICT facilitates the integration on interoperability requirements. The proposed interoperability architecture of IEEE Std 2030–2011 is illustrated in Fig. 1.1 that is revised from [8]. The architectural structure has been designed regarding Open Systems Interconnect (OSI) reference model that is used in Internet and cloud applications. The smart grid applications include automated meter

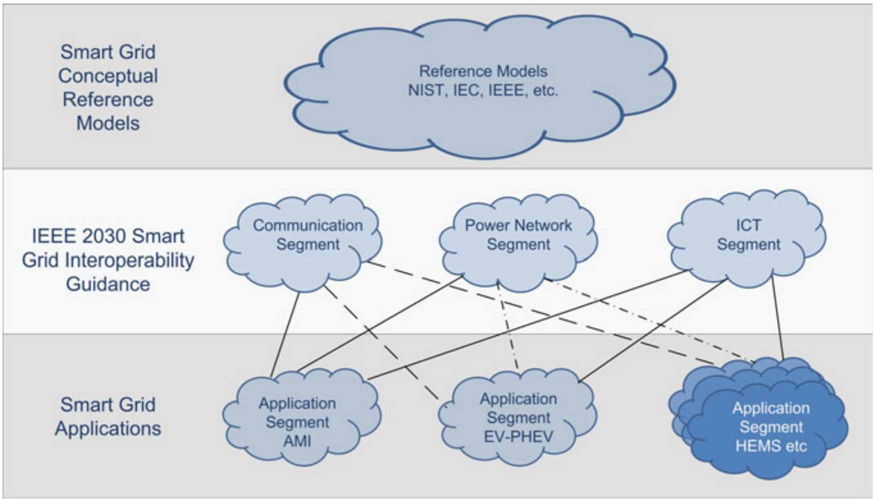

**Fig. 1.1** Smart grid infrastructure with its components

reading (AMR), advanced metering infrastructure (AMI), plug-in electric vehicles (PEVs), microgrid DR and DSM, phasor measurement units (PMUs), intelligent electronic device (IED) integration, supervisory control and data acquisition system (SCADA), substation automation, and remote monitoring systems.

The interoperability guidance layer of smart grid shown in the middle of Fig. 1.1 manages interaction along smart grid applications and smart grid conceptual reference models. A conceptual reference model of smart grid provides a set of views and descriptions to define features, behaviors, requirements, and standards for smart grid system. The conceptual reference models describe layer interactions and possible applications and usages in addition to actors, domains, and layered structure. Although several research institutes and organizations have proposed a number of reference models, NIST and IEC reference models are widely accepted in the literature [12].

The smart grid domains are defined as bulk generation, transmission, distribution, and customers at electrical flow level, and markets, operations, and service providers at communication flow level. The smart grid interacts electrical and communication levels by using a number of communication architectures including area networks, power system architectures of generation, transmission, and distribution, and ICT architecture providing integrity features to the existing systems as shown in Fig. 1.2 [12]. The bulk generation is comprised of generating power plants. The plant control systems are integrated with other domains over wide-area networks (WANs) and with substations by using local area networks (LANs). The transmission level includes substation devices, electric storage systems, field devices, and data collectors. The data collectors provide interaction along WANs, substation LANs, and field area networks (FANs) located in distribution domain. On the other hand, the field devices

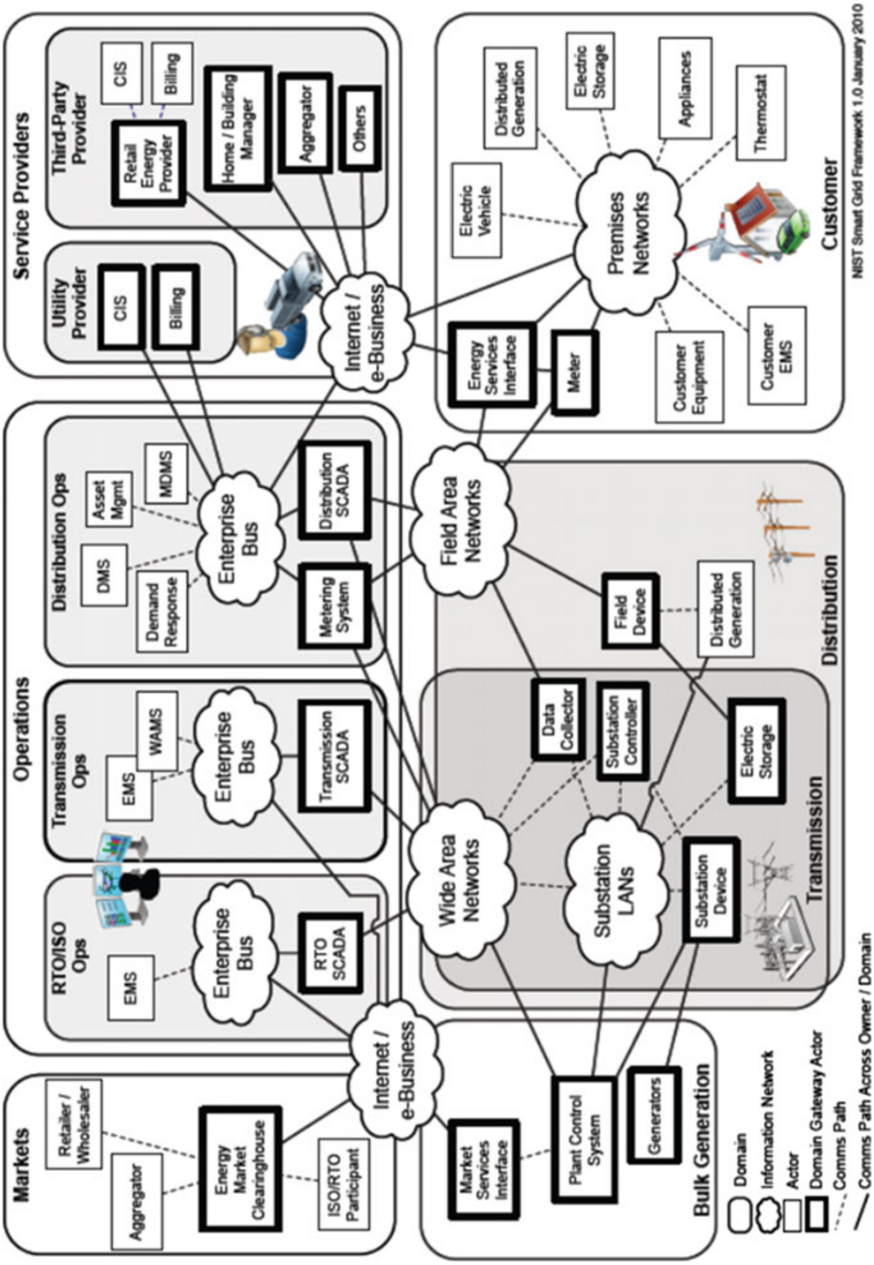

**Fig. 1.2** NIST conceptual reference diagram with ICT and power system [12]

communicate with operation and transmission domains by using FANs. The customer domain defines several residential applications and appliances such as DG sources, home appliances, PEVs, smart meters, energy management systems (EMSs), and electric storage systems (ESSs).

The customer domain interacts with operations and service providers. The communication interface is comprised of home area network (HAN), building area network (BAN), industrial area network (IAN), or FANs. The operation domain includes several operators such as regional transmission operator (RTO) and independent system operator (ISO), transmission operators, and distribution operators. These operators mostly communicate with power network domains by using SCADA systems integrated with enterprise buses that provides interface connection to several management systems. The transmission operators include wide-area measurement system (WAMS) in addition to EMS. The distribution operator controls the power network domains with distribution management system (DMS), metering data management system (MDMS), DR management and asset management systems. The customer information system (CIS), billing operators, data aggregators, and building management system are operated by service provider domain.

The energy market and utility grid operators have promoted the use of RES in order to manage increased demand on the customer side. Furthermore, governments and authorities encouraged the RES usage to compensate greenhouse gas emissions and to decrease the carbon emission. The wind turbines and photovoltaic (PV) power plants have been paid much attention among other alternative energy sources. The multi-megawatt plants have been installed in gradually increasing ratios, and the technological improvements have been triggered due to required operation and management services. Many governments provided incentives and enabled to shift DG approach at customer level that converted consumers to prosumers by installing their own microgrids (MGs). These improvements have led to enhance various DSM and DR programs by generation and distribution companies [1–3, 7]. In addition to DG and MG, ESSs have been widely required to provide a balance between generation and consumption demands. The technological innovations in terms of transmission, distribution, consumption, and monitoring sections are required as well as in smart generation. A wide variety and heterogeneous grid infrastructure and technologies are being used in smart grid improvements. A comprehensive smart grid infrastructure is illustrated in Fig. 1.3. The smart grid architecture has been shown with its all system integrations and components in the figure. The lower layers represent power system along smart grid. It visualizes each component at bulk generation, transmission, and distribution, energy storage, DG, and consumer sections. The bulk generation that is fundamentally composed by conventional sources such as CHP, nuclear, and hydroelectric power plants, and RESs such as wind and PV plants. The power networks are illustrated with red lines in the figure, while communication networks are dotted blue lines. The generation monitoring and control operations are performed at generation level by RTO and ISOs.

The transmission and distribution levels include lines, intelligent substations that can be managed remotely, monitoring and control automation system, and smart transformers that are equipped with sensors and IEDs. The intelligent substations

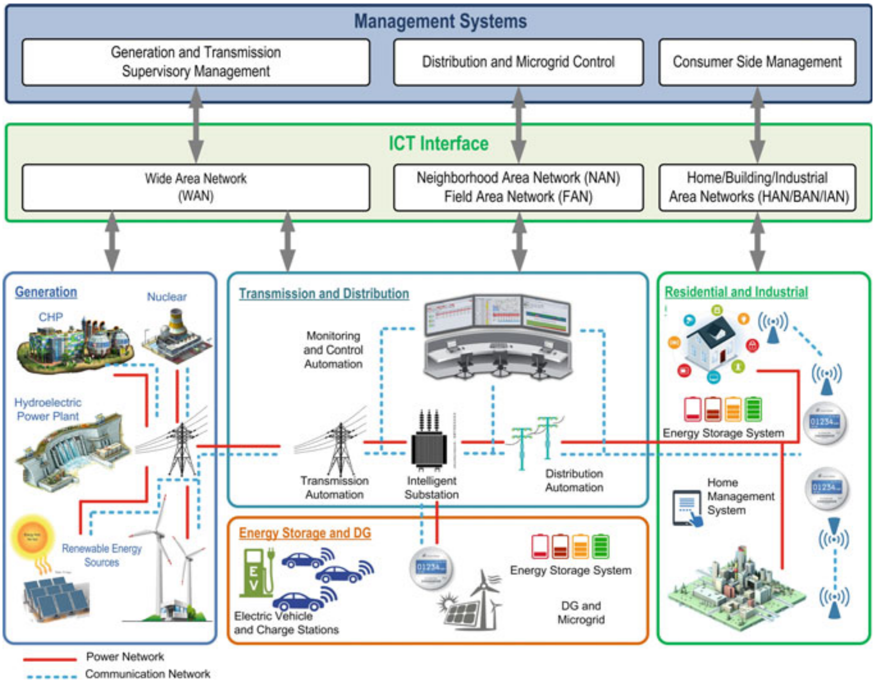

**Fig. 1.3** A comprehensive smart grid infrastructure with its components

interface energy generation and DG plants at distribution level. The EV charge stations, fuel cell- and battery-based ESSs, and microsources can be integrated to distribution system as well as in the consumption level. The residential and industrial loads comprise the consumption level of utility grid where entire communication infrastructure can be achieved in wired and/or wireless transmission systems. The residential loads can be managed by using home management systems (HMSs) in the context of smart grid applications that are supported by service providers. The supervisory and management systems are interfaced with power network by ICT sublayer.

The management system includes three essential sections that are supervisory management, control service, and DSM/consumer side management. The supervisory management section is responsible to perform monitoring and control duties for generation and transmission levels of bulk generation. This data and control signal transmission along these layers is performed with the aid of WANs. The distribution and MG control services are realized over NAN and FAN. The smart meters play a key role in the improvement of smart grid by the integration to the existing grid infrastructure. The smart meters are capable to provide two-way data flow and to operate control commands. The data transmission can be mostly carried out by wireless communication methods such as Wi-Fi-, GSM-, or IEEE 802.15.4-based technologies.

However, power line communication is another communication method that uses existing power lines as a transmission medium [1, 2, 7, 13].

First researches on smart grid have been focused on smart generation systems, plant installations, decentralized generation architectures, and interactive system implementations. However, security, sustainability, reliability, and efficiency are the most recent topics that are extensively being researched. It is noted that smart grid architecture is analyzed in three main aspects that are *infrastructure*, *management*, and *protection* [1]. The *smart infrastructure* studies include metering, smart devices, sensor networks, monitoring, and communication systems. The penetration shares of various sources, decentralized generation, and transmission are also handled in the infrastructure context. The smart infrastructure is widely classified into three subsystems such as smart energy subsystem, smart information subsystem, and smart communication subsystem. The smart energy subsystem defines advanced generation, transmission, and consumption environments as its name implies. The smart information subsystem allows to advanced metering, monitoring, and management of smart grid, while smart communication subsystem ensures connectivity and data transmission along applications, services, systems, devices, and components of smart grid [9]. On the other hand, *smart management* operations encompass energy efficiency, power quality, demand profile detection and responding, optimization, and control services. The communication and intelligence-based operations such as smart metering are also covered by smart management requirements. The *smart protection* is related to both power network and communication infrastructure in terms of reliability, security, failure detection, diagnostics, self-healing features, and cyber-physical security [1, 2, 9].

Consequently, smart grid improvement that is still being sustained procures a number of new technologies and components integrated to existing grid infrastructure. The most widely known and researched systems are RESs, DG sources, AMIs that are deployed at customer levels, smart measurement systems for active and reactive power detection, SCADA and improved control systems based on wired and wireless communication interfaces, and recent measurement and monitoring devices such as synchrophasors, PMUs, power quality analyzers (PQAs), and sensor networks [13]. A wide variety of grid services and functions have been improved in terms of smart grid operations, and legacy applications have been enhanced to adapt conventional grid to intelligence-based operations. Furthermore, various communication infrastructures have been developed to ensure the quality and reliability of data transmission in the context of monitoring, metering, and control applications.

This book is comprised of two parts that the first one presents smart grid technologies on hardware and power sections, while the second part includes emerging communication systems for smart grids. The first part presents smart grid requirements, power network interaction, technical enhancements, energy storage applications, DSM and DR programs, and potentials in smart grid. The second part of this book focuses on smart grid communication systems and standards, novel and potential communication technologies for smart grid, optical communication methods, Internet of things (IoTs), power line communication (PLC), IEEE 802.15.4 technologies, cyber-security tools and applications in smart grid. Thus, this chapter is arranged to provide a kind of summary of whole book.

This chapter covers presentation of essential components of smart grid such as sensor networks, smart monitoring and control features, security requirements, reliability conditions, standards, regulations, and quality of service. The smart grid applications and requirements are surveyed in the following subsections. The applications are analyzed in the context of power network as AMI, DR, station and substation automation, and DER infrastructures. There is a featured communication subsection which is also presented in the following of this chapter. The wired and wireless communication technologies that are widely used in smart grid applications are presented in detail. Furthermore, the area networks are presented in a logical fashion starting from bulk generation to consumer side. Each of these components is reviewed and is presented in terms of challenges, improvements, and contributions in the following subsections.

## 1.2 Essential Components of Smart Grids

The power and communication network of smart grid requires some featured and essential components to allow performing monitoring, measurement, and control operations. These components are required to ensure power network stability, microgrid and substation automation, communication reliability and security, protection of entire system, and sustainability. The components used in smart grid infrastructure are a combination of intelligent devices, appliances, and subsystems that play a vital role in generation, transmission, and distribution of electricity.

The novel components can be completely new or advanced types of legacy devices. They are related to power electronics and communication systems where the advanced power electronics components include semiconductors, superconductors, and advanced devices increasing efficiency and reliability of power systems. The smart metering components are equipped with sensors and sensor networks. They are convenient to detect blackouts, power quality deficiencies, real-time generation and consumption rates. The smart substations that are comprised of transformers, circuit breakers, capacitors, and switches are located in the distribution network to monitor system performance and to supply the local loads.

The synchrophasors and PMUs are advanced components of smart grid since they play key roles in SCADA and energy management systems. These components provide interactive and instant monitoring of entire system with event analyses. They also provide a number of detection routines to detect rate of change of frequency (RoCoF), islanding, and voltage stability. They are based on GPS-enabled data acquisition features and perform data transmission to monitoring center. The protection components of smart grid are used at any level including generation, transmission, distribution, and communication sections. They ensure power or data protection regarding the section that they are located. POAs and PMUs provide power protection by supplying measurement data to predict deficiencies on power and voltage magnitudes, phases, and frequencies. The data protection and privacy requirements are also ensured in the context of smart component utilization. The essential components of smart grid are presented as follows.

### 1.2.1 Smart Sensors and Sensor Networks

The power grid and communication network of smart grid that have been illustrated in Figs. 1.2 and 1.3 are integrated a number of conventional and novel sensors called smart sensors. The smart grid interactions are managed by the measured signal and data from these sensors and the networks that are comprised of sensors. The smart sensors and sensor networks facilitate to construct reliable, secure, and efficient management infrastructure in the context of smart grid applications. A sensor is a device that responds to physical, electrical, or magnetic input signals and produces an output magnitude in current or voltage waveform. A number of common sensors such as voltage transducers, current transducers, phase and flux sensors, pressure sensor, power quality transducers, irradiance sensors, anemometers, frequency sensors are widely located in generation, transmission, and distribution levels of power network. Furthermore, featured temperature, humidity, pressure, proximity, lightning, capacitive and magnetic sensors, energy meters, and smart meters are used in smart home management systems in order to provide more comfortable and secure living standards at customer level [7, 14].

Sensors and sensor networks play a crucial role in metering, monitoring, and remote measuring applications. The equipments that are used as sensors can be in resistive, capacitive, magnetic, piezoelectric, and similar types [7, 15, 16]. The fundamental smart grid sensors are voltage sensors, current sensors, power meters, and PQAs. The voltage and current sensors can be based on series and shunt resistors for low-cost applications or Hall effect-based devices for precise and isolated applications. Figure 1.4 shows Hall effect sensor-based voltage and current measurement circuits with signal conditioning section in Fig. 1.4a, b, respectively [2]. These devices are used in any section of generation, transmission and distribution networks to measure the actual voltage and current waveforms. The acquired voltage and current magnitudes are converted to dc voltage levels by operational amplifier circuit networks where signal amplifying, filtering, and true rms to dc conversion operations are performed by low-cost solutions. The conditioned signals can be transmitted to analog–digital conversion (ADC) ports of any microcontroller to process the measurement data.

The inherited measurement signals are processed in microprocessor for several data storage and communication purposes. The serial communication ports of microprocessors provide modulated signal output to transmit measured signal in wired or wireless communication mediums such as universal serial bus (USB) or IEEE 8012.15.4-based wireless systems. A data storage and monitoring infrastructure for PV panels has been presented in [17] where the measured voltage and currents are transmitted to a microcontroller and inherited data are modulated for USB transmis-

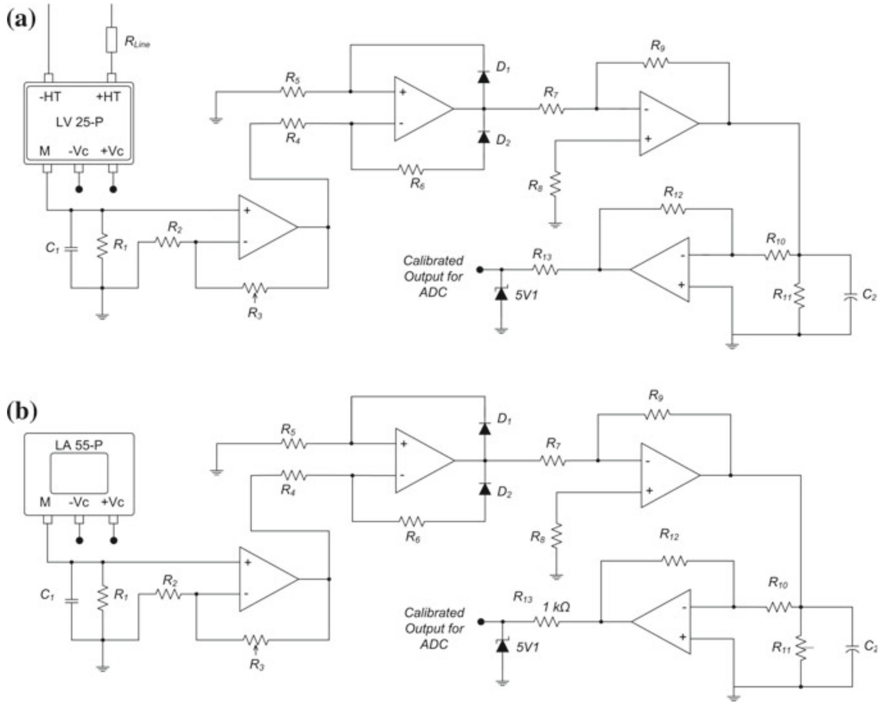

**Fig. 1.4** Voltage and current sensors with signal conditioning circuits, **a** Hall effect voltage sensor, **b** Hall effect current sensor [2]

sion to a computer. The measurement data acquired from USB port of computer are stored in a database file and then processed by a operation software that provides graphical user interface (GUI) for users or operators.

While this sensor and signal conditioning devices are convenient to use in dc power monitoring, it is also possible to design conditioning devices to detect maximum and root-mean-square (rms) magnitudes, phase, and frequency components of ac waveforms. Such a system has been illustrated in Fig. 1.5 where a combination of Hall effect sensors is for current measurement and shunt resistors are for voltage measurement. This circuit differs from previous one in a few points. One of them is that it requires single power supply at +5 V, while the previous one requires symmetrical supply due to Hall effect sensors and operational amplifier type. However, the rail-to-rail operational amplifiers are capable to operate with a single supply voltage that is compatible with microprocessor supply, and thus, additional power supply requirement is eliminated. In addition to this, the Hall effect voltage sensors are substituted with shunt resistors that are based on voltage-divider theory. The proposed circuit diagram by Kabalci decreases cost of measurement device and signal conditioning network in Fig. 1.5 [2]. The current sensor produces dc-biased ac output voltage in the circuit. On the other hand, a voltage sensor network is comprised of ac

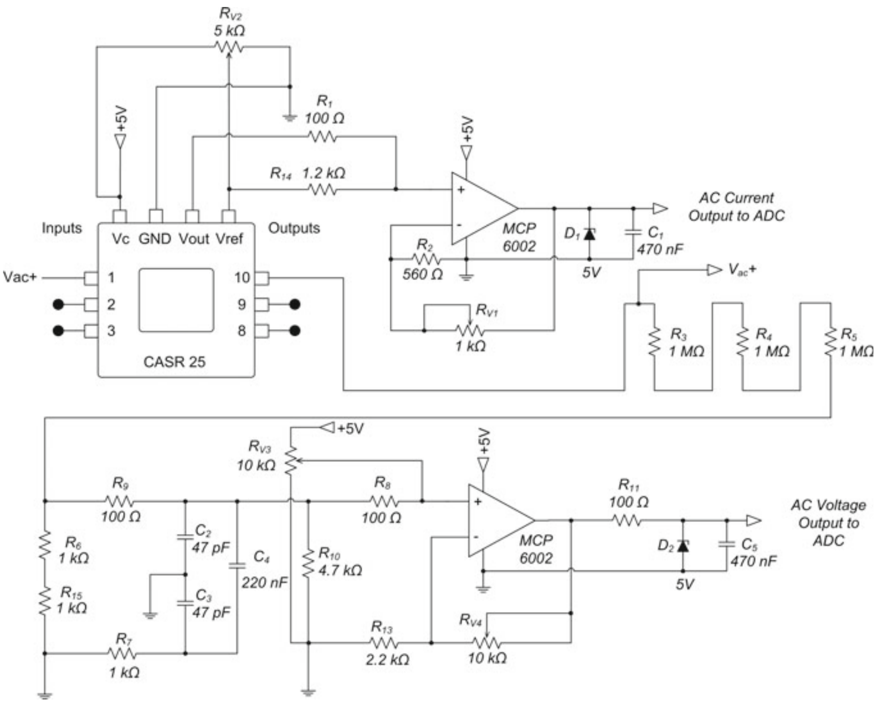

**Fig. 1.5** Voltage and current sensors with signal conditioning circuits for ac measurement [2]

line and virtual ground is comprised of neutral point of capacitors seen in the lower left-hand side of figure.

Another voltage and current measurement method uses potential transformers for voltage and current transformers that are implemented in the similar theory of regular Hall effect sensors but operates at high voltage and high currents. The potential transformers are a kind of decreasing or step-down transformers with their ferromagnetic core and predefined turns ratio. It is possible to find potential transformers ranging from 70 up to 800 kV, while Hall effect sensors can be used utmost 5 kV [7]. Therefore, the potential transformers are much more compatible to be used in generation and transmission systems, while Hall effect sensors are convenient at distribution level.

The power meter and PQAs are deployments of fundamental voltage and current sensors that are widely used in smart grid applications. These metering devices are composition of fundamental sensors, and they play important roles to monitor and to measure the power quality of power network. These are mostly equipped with internal communication systems, and several recent communication protocols can be used such as Ethernet, USB, or RF. The use of power meter and PQA provide outage prevention due to their instant and continuous metering data transmission. Thus, outage and curtailment prediction programs can be operated in low-voltage (LV) and medium-voltage (MV) networks. Although the fundamental sensors are widely deployed in smart grid applications, there a number of featured smart metering and monitoring devices which have been improved. The smart metering and measurement systems that can be assumed as particular sensors for smart grid are presented in the following sections.

### *1.2.2 Phasor Measurement Units*

The most recent improvements in sensor technologies have advanced smart sensors used in smart grid applications. The widespread regulations and advances in energy policies required several developments in power networks and wide area monitoring, protection, and control (WAMPAC) issues. The smart metering and measurement devices that are advanced with recent developments in smart grid applications are PMUs, IEDs, and smart meters. The IEDs are used to detect faults, protection relaying, event recording, measurement, control, and automation aims in power network [16, 18].

The PMUs play a quite important role to monitor long transmission lines and integration to MV and LV distribution networks. A simplified block diagram of a PMU is shown in Fig. 1.6. The PMU includes analog inputs and data acquisition interface in order to inherit measurement data that are supplied to microcontroller. The global positioning system (GPS) receiver and internal phase-locked loop (PLL) ensure synchronization of entire system with universal time-coordinated (UTC) time stamp. The GPS-based timing is required to provide secure transmission in a WAMPAC system. Thus, the synchronized phasor measurement of voltage, current, phase, frequency, and RoCoF is ensured. This feature of PMU tackles regular SCADA applications in terms of synchronization and reliability of the measure data. The PMUs provide around 60 samples per cycle that is fifteen times higher than SCADA.

A sample measurement of a cosine wave to detect the phasor degree and phasor representations have been illustrated in Fig. 1.7a, b, respectively. The PMU detects the Vmag parameter that is root-mean-square value of measured voltage and/or current waveform and phase angle, $\phi$, regarding reference phase as given in following equations:

$$v(t) = V_{\mathrm{m}} \cos(\omega t + \phi) \tag{1.1}$$

$$V(t) = \frac{V_{\mathrm{m}}}{\sqrt{2}} \angle \phi \tag{1.2}$$

The calculated phase angle is defined as synchrophasor that is detected at any time of the measurement and tagged with a timestamp regarding UTC time [7, 19, 20].

IEEE C37.118.1-2011 standard describes PMU measurement requirements such as synchrophasor and frequency detection operations. In addition to these, the stability parameters as total vector error (TVE), timing reference, signal timing, frequency

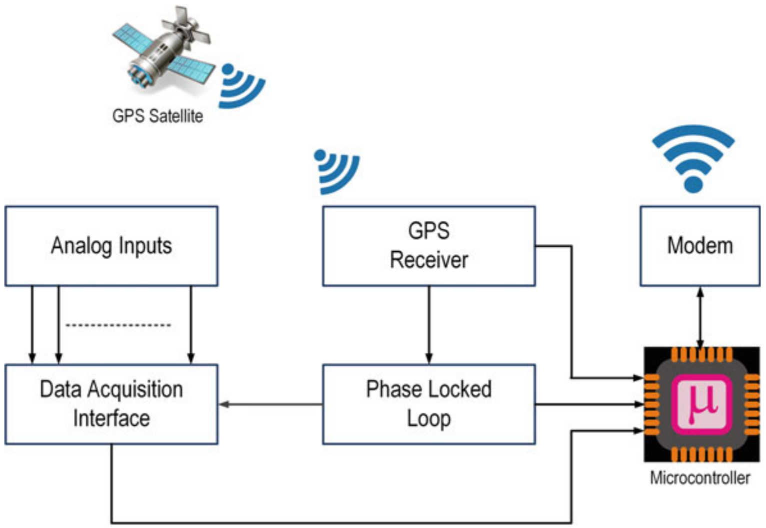

**Fig. 1.6** Basic block diagram of a PMU

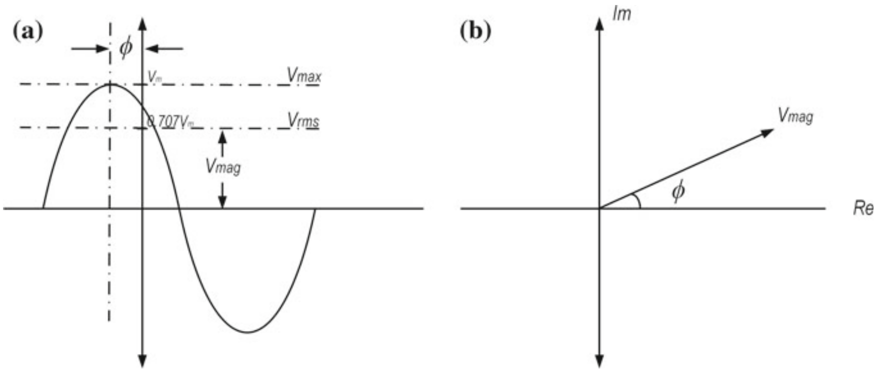

**Fig. 1.7** Phasor measurement of a cosine wave, **a** voltage waveform, **b** phasor representation

error, and RoCoF errors are also listed in the standard [19, 20]. The TVE is calculated as a combination of magnitude and phase angle errors that allowed maximum TVE value is 1%. The calculation method of TVE is given as follows [19]:

$$TVE = \sqrt{\frac{(\hat{X}_r - X_r)^2 + (\hat{X}_i - X_i)^2}{X_r^2 + X_i^2}} \tag{1.3}$$

where $\hat{X}_r$ and $\hat{X}_i$ are estimated phasor, and $X_r$ and $X_i$ are reference phasors [19]. A PMU system should ensure some standards and requirements at the output regarding IEEE C37.118.1-2011 standard. The timing and synchronization signals should highly comply with UTC, and the data transmission speed should be high enough to prevent latency. On the other hand, highly accurate processing algorithms are required to detect and to report phasor values of voltage, current, phase angle, RoCoF, and frequency value. The PMUs should provide secure, accurate, and highly reliable communication signal to monitoring center by considering standard message frames and headers [20, 21].

### *1.2.3 Smart Meters*

The advances of smart grid have also increased researches and improvements on smart metering in the context of power network and communication infrastructure enhancements. These advances have been triggered by recent ICTs, monitoring and measurement requirements, and improved sensor technologies. It is noted that communication and measurement requirements play a vital role in smart grid improvements as well as power network novelties. The smart metering systems include AMR, AMI, and automatic meter management (AMM) applications that are developed regarding conventional metering systems [1].

The smart meters, namely watt-hour meters, are based on voltage and current measurements due to related sensor networks. The measured and conditioned signals are converted to digital signals to generate measurement data that are used to be stored and transmitted to remote monitoring and operation centers. Thus, remote monitoring, measurement, control, and decision-making can be realized by using two-way communication and power transmission. Besides transmission system operator (TSO) and distribution system operators (DSOs), customers can be capable to monitor and manage their smart household appliances by using user interface of smart meters. The advanced smart meters enable users to manage reclosers, switches, and relays to control energy consumption or to operate devices. The fundamental responsibility of smart meters is to measure the energy consumption of entire system where they are connected, to store consumption data, and to transmit the stored data to DSO periodically. The smart meters provide several advantages and management opportunities to consumers and to DSOs. For example, smart meters can rapidly detect or predict the blackout situations and provide restoration services to DSOs and consumers. On the other hand, smart meters comply with DSM programs of DSOs by detecting and coordinating daily use priorities and provide cost saving for consumers. Smart meters provide secure and reliable communication in terms of integrity, authenticity, and privacy issues for transmission link between customer and DSO [22, 23].

The smart meters provide several advantages for DSOs such as fraud prevention, usage identification, detailed DSM programs, and almost fully efficient management of entire distribution system at each node. The DSO can inherit distributed and consumed energy rates in a power network and can detect any fraud or loss in the distribution network by comparing distributed and consumed energy rates. The smart meters can provide consumption logs by daily and 10–15-min intervals. On the other hand, instant access to smart meters is also available to perform relaying or switching at the node. Almost all of recent smart meters are equipped with in-home displays and Internet-based user interfaces to enable consumers to track their instant energy consumption. Thus, consumers are encouraged to save energy by decreasing waste consumption [24, 25]

Block diagram of a three-phase four-wire smart meter has been illustrated in Fig. 1.8. The first section of a smart meter is its grid interface where the current and voltage sensors are located. These sensors detect the current and voltage magnitudes, and metrology section converts the measured values to conditioned signals by using circuits as shown in Figs. 1.4 and 1.5. The signal conditioning devices produce output signals that are compatible with ADC port of any microprocessor. The phase and frequency detection capabilities are also inserted to most of recent smart meters. The microprocessor acquires the measurement data over its ADC ports and then stores the processed data at internal database. The communication interfaces are also managed by microprocessor with its serial and parallel communication interfaces as shown in the right-hand side of Fig. 1.8. Most of smart meter microprocessors are equipped with infrared and RFID communication interfaces in addition to Ethernet, CAN bus, RS232, RS485, and wireless communication capabilities. Thus, they can be integrated to HAN, BAN, IAN, and WAN networks.

The WAN networks are used by DSOs for billing, monitoring, and DSM aims while HAN provides to connect to smart household appliances, Internet gateway, and home energy management systems [23]. In addition to wireless communication systems, wireline communication systems such as power line carrier (PLC) communication can be used to connect smart meters. It is based on data transmission using existing power lines as a transmission medium. The power lines are capable to provide two-way data transmission in addition to two-way power transmission. These communication methods are introduced in the following sections of this chapter.

The data management at the monitoring and control center is a crucial task for DSOs to produce billing data, management, and control operations. The core of control system is comprised of metering data management system (MDMS) that includes outage or blackout management system (OMS), customer information system (CIS), geographical information system (GIS), and data management system (DMS) [1].

The OMS tracks the power quality and related parameters of customers to predict any outage may occur or not. The prediction data are generated at logical RoCoF situations, extremely low or high voltage, and high current drawing states. The OMS triggers MDMS at emergency to protect entire grid management. The GIS and CIS are used to data acquisition and identification of the acquired data from customers to detect exact location and consumption values, and to process correct billing data [1].

### *1.2.4 Wireless Sensor Networks*

The legacy SCADA system is comprised of two kinds of networks including control and corporate networks. The control network is used to perform field measurements

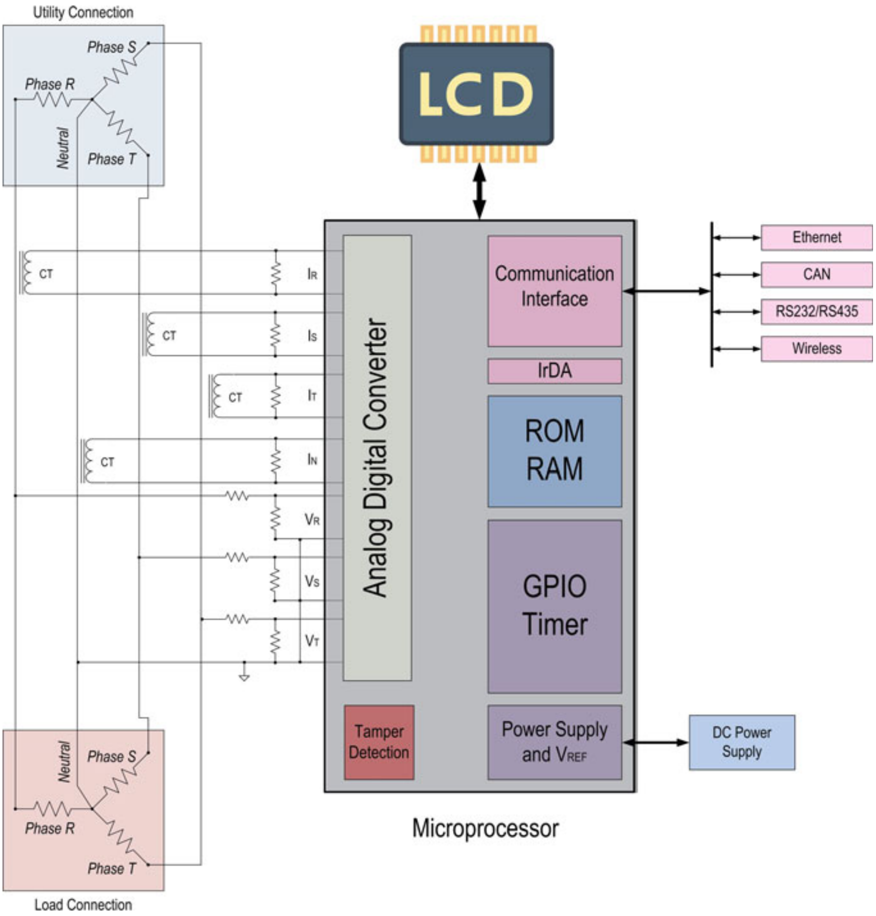

**Fig. 1.8** Block diagram of a three-phase four-wire smart meter

and data acquisition, control operations, substation and remote station monitoring, and interaction with remote terminal units (RTUs). On the other hand, the corporate network defines the monitoring and control center, and supervisory area. Therefore, a SCADA system is equipped with several sensors and transducers to detect each measurement value and to monitor the magnitudes of required systems. The measurement signals are transmitted to monitoring center by using Modbus/TCP connection and industrial communication protocols. An architectural block diagram of a SCADA system is shown in Fig. 1.9 [26]. The communication system is based on combination of tunneled wireline and wireless communication infrastructures that all are operated regarding secure transmission protocols. The wireless communication methods are widely accepted as low-cost, secure, and efficient transmission systems in wide-area communications since they facilitate to transmit signals to long ranges in a secure and reliable way. The widely used industrial wireless communication

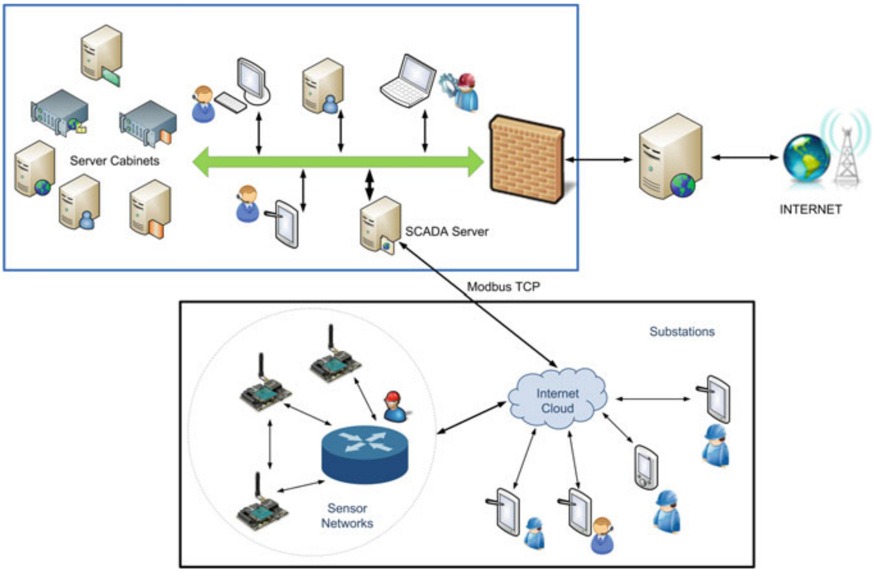

**Fig. 1.9** Architectural system of SCADA networks

systems are ZigBee Pro, ISA100.11, and WirelessHART that are based on IEEE 802.15.4 standard and used in wireless personal area networks (WPAN) [26, 27].

The recent industrial and smart grid communication systems are equipped with wireless sensor networks (WSNs) that are comprised of numerous sensor nodes, and they have different characteristics from conventional sensors. The sensor nodes in a WSN are equipped with several hardware features such as RAM, ROM, central microprocessors operating at exact frequencies. The smart sensors along a WSN can measure electrical and physical magnitudes such as voltage, current, frequency, temperature, pressure, vibration, irradiance. The wireless sensors require a battery or another energy source to operate that lasts up to ten years. These devices are quite smart due to their autonomous operation and energy harvesting features that enables them to sustain operation for long years. Furthermore, they have been designed with self-healing, self-monitoring, and automatic configuration capabilities that allow them to interact with cyber-physical environments [26, 29, 30]. In addition to environmental monitoring applications, WSNs have found widespread use in smart grid due to their intelligent services and interfacing features for power grid. They are being extensively used in home energy management systems (HEMSs).

The smart appliances and residential devices that are equipped with WSNs are capable to be monitored and controlled by wireless communication systems. On one hand, it has been noted that around 65 million residential device will be integrated with smart meters until 2015 in the USA [31]. On the other hand, smart grid applications are much more than the residential devices and smart appliances. The industrial and power network utilities are responsible of greater share in energy generation and consumption levels. Therefore, smart meters, AMI applications, DSM, DR, dynamic billing, fault detection and restoration devices, load control systems, DG, distributed energy resources (DERs), remote control devices, and remote automation appliances have extensive potential in terms of WSN applications [29, 31]. The AMI implementation is analyzed in three phases that the first one was AMR applications. The second phase of AMI development includes time of use pricing services, DSM and DR policies, AMI deployments, and load and outage control technologies. The third and existing phase has brought real-time pricing and two-way energy transmission services. The microgrid improvements, fault prediction methods, use of smart appliances and plug-in hybrid electric vehicles (PHEVs), DER utilization, automated generation, and DG have accelerated the developments in the third phase. The intelligent services and technologies have been enabled by enhanced communication methods covering wireless and Internet-based technologies. The smart grid road maps are being planned considering aforementioned technologies and WSN interaction [29].

The WSN applications along power network are given in Table 1.2 considering each level such as generation, transmission, distribution, and customer levels. The remote monitoring and control applications listed in the table require any kind of area network according to utilization area such as HAN, IAN, FAN, and WAN. The generation-, transmission-, and distribution-level applications are located in geographically widespread areas. Therefore, field monitoring and control operations require IAN, FAN, and WAN communications. On the other hand, smart home appliances and HEMS located in consumption level require HAN to get devices communicate with central system, and WAN to be reached from any location [30–32].

The communication security of WSNs should be taken into account while installing remote monitoring and control nodes. The attacks and intrusions are classified as active and passive attack for WSNs. The intruders hide themselves in passive attacks and intend to inherit data, monitor the transmission signals, and try to demolish operation of devices located at the end of nodes. The most widely known passive attacks are eavesdropping, tampering the node, demolishing the operation, and traffic analysis. In active attacks, the intruder targets to change the operation and function of attacked system. The intruder is visible in this attack type, and thus, it can be prevented to protect network security. Besides the most widely Denial-of-Service (DoS) attacks, jamming, flooding, blackhole, worm, and sink attacks can be listed in the context of active attacks. The protection methods are listed as prevention, detection, and mitigation [33]. The WSNs and security issues are presented in detail in the following sections of the book. Another introductory section of this chapter is on smart grid applications and requirements of the applications. The sensor networks and WSNs provide enhanced application portfolio for smart grid applications. The related applications are summarized in each level of power grid including generation, transmission, distribution, and consumption in the following subsection.

**Table 1.2** WSN applications in smart power grid

| Power network level | Applications |
|---|---|
| Generation | Remote monitoring |
| | Power quality analyzing |
| | DG and DER monitoring |
| Transmission | Overhead transmission line monitoring |
| | Underground line monitoring |
| | Power quality analyzing |
| | Outage detection |
| Distribution | Substation automation |
| | Fault detection and restoring |
| | Direct load control |
| | AMI and AMR |
| | Underground cable monitoring |
| | Smart transformer monitoring and control |
| Consumption | WPAN applications |
| | HEMS |
| | Microgrid monitoring |
| | PHEV monitoring |
| | Building and smart appliance automation |
| | DSM and load control |
| | Wireless AMR |

## 1.3 Smart Grid Applications and Requirements

This section presents smart grid applications in power grid regarding each level of generation, transmission, distribution, and consumption. The sensing devices and sensor networks have improved the measurement, monitoring, and control capabilities operated in the power grid levels. Although each level has its featured applications, the smart metering is required at any level of power grid network. The smart metering applications include DR programs, load profiling, automatic load control, outage detection, consumer metering and power quality detection, DG monitoring and control, remote control, and instant metering applications [5, 7]. The DR and DSM programs are implemented by TSO and DSOs regarding metering data inherited from a region or an exact node located at consumer section. The DR programs allow decreasing, spread to different times, and manage electricity consumption according to predefined tariffs and timescales. The directed consumer behaviors can decrease the waste use of electricity. On the other hand, it provides managing option for demand peaks and facilitates to manage total demand [34].

The generation-side applications require widespread voltage, current, and frequency sensors to monitor generation units and energy conversion devices. The sensors can be featured electrically, mechanically, or magnetically regarding operation systems. The generation sources can be one or combination of conventional sources such as CHP, fuel-based plants, hydro plants, or RESs including wind, solar, and biomass. The fuel-based plants particularly require several measurement and monitoring interfaces to detect fuel level, fuel quality, pressure, and temperature sensors. The generation and transformation sections in any generation unit either conventional or renewable require similar measurement transducers such as voltage and current sensors, power meters, PQA, frequency sensor, speed and temperature sensors. Wind turbines are particularly equipped with pitch angle sensors, torque sensors, speed sensors, anemometers, and gearbox transducers [7]. The generation-level applications include remote monitoring of wind and solar plants, distributed generation, and power quality monitoring that all are based on use of sensor networks or WSN. The measurement infrastructures are implemented to monitor DC and AC power networks [23].

Overhead lines, transformers, underground cables, and substations comprise the transmission systems. The current, voltage, and temperature sensors are used at all components of a smart transmission system for remote monitoring and control aims. On the other hand, there are particular sensors such as lightning sensors, partial discharge sensors, and conductor motion sensors are required to monitor overhead lines and transformers. The substations should be equipped with PQA, power meters, frequency sensors, and PMUs in addition to regular sensor devices. The underground cables require insulation sensors in addition to other sensors.

The transmission system plays a crucial role in utility grid since they connect distance stations and substations with generation system. Since the current transmission systems and substation have been gradually aged, there are numerous challenges for transmission systems. These include increasing the capacity of current transmission system, increasing integration of DG systems and advanced power electronics, penetration of RESs that causes intermittency and curtailments. These challenges are tackled by the use of smart grid applications such as outage detection, fault circuit indicators (FCIs) and line monitoring systems for overhead and underground transmission cables, fault detection and diagnosing devices, particular discharge control and monitoring applications [7, 23].

The conventional distribution system was responsible for delivering power provided from generation and transmission system to consumers. However, the recent distribution system is capable to provide two-way power delivery where the consumers have been transformed to prosumers due to microgrid applications and regulations. Therefore, distribution system requires widespread monitoring and measurement in the context of smart grid applications. The AMI and remote monitoring studies have been extensively researched due to increased variability of power electronics and communication features of distribution and consumption levels. All the measurement and monitoring systems are equipped with sensor networks, transducers, WSNs, and energy management interfaces. The prominent smart grid applications include wireless AMI, automated management systems, HEMSs, building automation devices, DSM, and DG monitoring in distribution and consumption levels [3, 7, 23, 35–39].

The featured smart grid applications related to four levels of power network are introduced in the following sections. They are presented in brief since there are several aspects of these applications which have been given in the following chapters.

### *1.3.1 Advanced Metering Infrastructures*

The distribution management system (DMS) is a control infrastructure required at distribution level to monitor system parameters. The conventional DMS provides two-way signal transmission that is conventionally based on SCADA system. The advanced AMR and AMI applications provide two-way data transmission to connect millions of smart sensors and smart metering devices comparing to limited capability of SCADA. Besides, AMR and AMI enable high-speed communication. Although several metering infrastructures have been improved, AMI was accepted as the most featured two-way communication and monitoring infrastructure among others. It is noted that the main challenges of AMI and DMS integration are caused by different communication methods operating on the same platform, and continuously changing AMI load types [40]

However, AMI is the most appropriate and in-use smart metering technology in residential and industrial measurement applications interacting with utility grid. The smart meter connects to the monitoring center with several communication methods. The CPS of AMI is comprised of several systems as shown in Fig. 1.10 where the consumer nodes are equipped with data concentrators. The meter data management system (MDMS) is located in the heart of operation center that includes customer information system (CIS), outage management system (OMS) , geographical information system, and distribution management system (DMS) [41].

The centralized AMI operation shown in Fig. 1.10 is shifted to decentralized topologies by several researches. Zhou et al. have proposed a decentralized MDMS system that decreases the communication and operation cost owing to distributed operation centers as shown in Fig. 1.11. Such a distributed operation center approach the data bandwidth is required for data transmission along central and decentralized operation centers [41].

The communication infrastructure is comprised of power line carrier (PLC) systems in the context of wired communication or by IEEE 802.15.4-based networks and WPANs. The AMI system is responsible to transmit the data about measured power consumption, power factor, energy demand, billing data, and user ID for identification [42]. The cyber-security and reliability of smart meters based on AMI architecture are being extensively studied that is also presented in a chapter in the contents of this book. The critical features of a smart meter can be noted as time-based pricing, energy consumption measurement and data storage, fault and outage detection, remote control capability, load control for DRM, power quality measurement and monitoring, power factor detection, energy theft prevention, and interacting with several other smart devices [43].

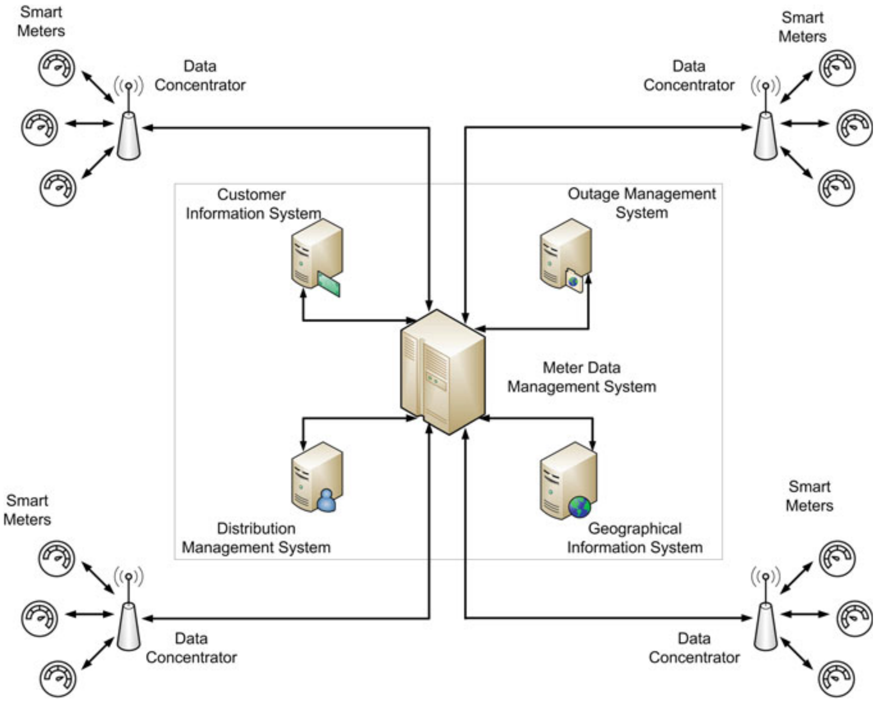

**Fig. 1.10** A centralized AMI infrastructure and components along smart grid

Manbachi et al. have proposed an illustration comparing centralized and decentralized volt-VAR optimization (VVO) application in smart grid system where the remote monitoring and measurement infrastructure were realized by using AMI [44]. VVO is a method that is used to control, monitor, automate, and optimize the distribution network by regulating the distribution node voltages provided by AMI system, and thus, it decreases the distribution losses. A VVO system uses several equipments including on-load tap changer of transformer (OLTC), voltage regulators (VR), and switchable shunt capacitor banks (CB) . The VVO applications can be either centralized that has been widely used for several years, or decentralized that is a recent approach.

The centralized VVO locates the control system in the center of processing. The most important drawback of centralized AMI is data flow rate as in centralized AMI system shown in Fig. 1.12. The amount of data that are provided by several nodes to VVO operation center increase as an avalanche and may cause several failures, intermittencies, and unsecure data transmission. On the other hand, the centralized VVO requires GIS system to locate each node in the mass. The decentralized VVO system overcomes most of the challenges occurred in centralized VVO. Decentralized VVO utilizes local controllers to perform optimization processes. Thus, the data transmission is inherited from local distribution feeders. A diagram comparing centralized

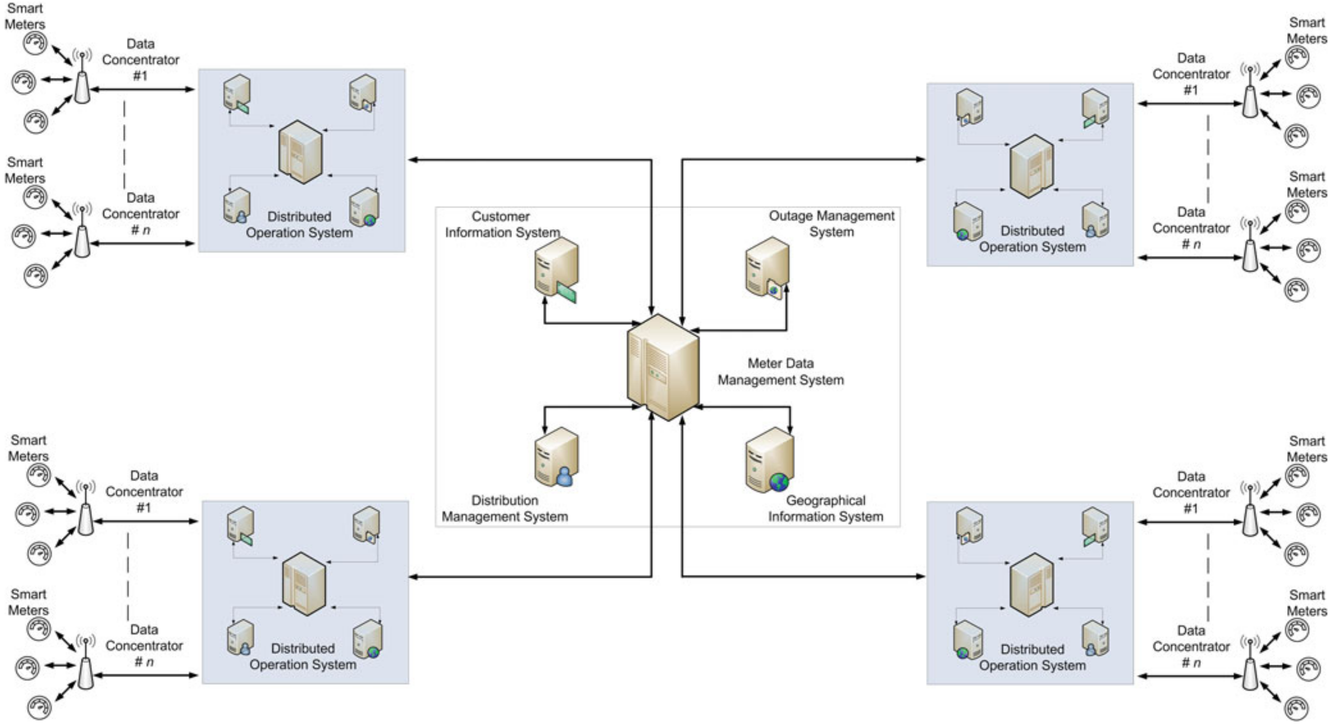

**Fig. 1.11** A decentralized AMI architecture and distributed operation centers in smart grid

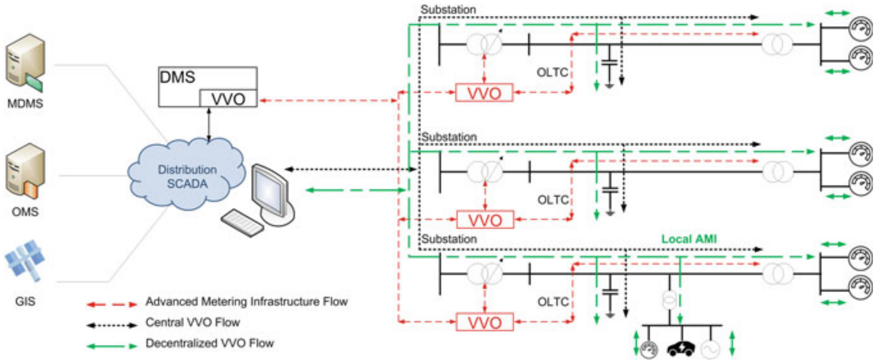

**Fig. 1.12** AMI-based centralized and decentralized VVO applications in smart grid

and decentralized VVO systems based on AMI infrastructure is shown in Fig. 1.12 [44]. The decentralized VVO does not require any of MDMS, OMS, and GIS, while they all are required in centralized VVO that is illustrated with dotted black lines.

The measurement data obtained from distribution nodes are transmitted to management systems by using distribution SCADA and DMS that includes a VVO section. However, decentralized VVO control method performs management by using only DMS system. The communication methods and applications used in AMI infrastructure are presented in the following chapters in this book.

### *1.3.2 Demand Response*

Numerous studies and researches on flexible and resilient utility network have been reported in the literature. There are several researches have also been performed in order to increase the flexibility of smart grid. The DR is a common topic in this context. The DR refers to manage and change consumption behaviors of customers in order to increase grid efficiency. The conventional grid applications do not provide an incentive or payback opportunity. Under these circumstances, customers are not aware of efficient energy consumption and DSOs are forced to manage utility grid by sustaining the balance between generation and consumption. However, DR programs contribute to grid management by incentive- or price-based programs in smart grid. The consumers are classified into three categories regarding their consumption profiles. The first group consumers do not change their behavior in peak hours or other times. The second group changes their peak demand times to off-peak hours when the energy cost becomes quite high during peak-load times. The third group covers few consumers that change their energy use times at peak-load times [25, 45].

The incentive DR programs are capable to control customer loads in peak hours or emergencies, and customers obtain incentives by permitting this. The load control profiles are direct load control (DLC), interruptible load, demand bidding, buyback,

**Table 1.3** A comparison table of DR programs and application features

| DR approach | Program type | Dispatch rule | Activation period | Activation trigger |
|---|---|---|---|---|
| Direct load | Incentive-based | Dispatchable | On demand | Event-based |
| Interruptible | Incentive-Based | Dispatchable | On demand | Event-based |
| Demand bidding | Incentive-based | Dispatchable | On demand | Event-based |
| Emergency | Incentive-Based | Dispatchable | On demand | Event-based |
| Time of use (TOU) | Price-based | Non-dispatchable | Hourly in a day | Periodic |
| Critical peak pricing (CPP) | Price-based | Both | On demand | Event-based/periodic |
| Real-time pricing (RTP) | Price-based | Non-dispatchable | Arbitrarily | Periodic |

and emergency demand reduction in incentive-based DR programs. The price-based DR programs intend to change customer behavior owing to price changes and reductions. The load control belongs to customer, and DSO cannot interfere with customer-side load. The price-based DR programs are based on time of use (TOU), critical peak pricing (CPP), real-time pricing (RTP), and inclined block rate approaches [25, 46, 47]. The price-based DR programs ensure customer privacy, but it requires a detailed schedule technique to manage load-side and generation-side demands. A comparison of DR programs and application features has been listed in Table 1.3 regarding the literature [46, 47].

The incentive DR programs are based on dispatchable rule operation, while the price-based programs are operated with non-dispatchable rules. On the other hand, all types of incentive-based methods are activated by events or causative situations, and they can be activated at any time when it is demanded. The price-based DR methods are activated periodically or arbitrarily as shown in Table 1.3.

### *1.3.3 Substation Automation Systems*

The enhanced distribution network includes many renewable plants and loads with novel technologies such as electric vehicles, smart devices, and communication interfaces. A high number of IEDs are integrated to smart grid infrastructure in industrial and residential use areas. The improvement of smart grid intensely requires several changes in design and configuration of substations that are used to integrate several nodes such as transmission lines, transformers, generators, compensators, and loads. The substations play a vital role for monitoring, communication, control, and management of power network in a widespread area. Therefore, the automation system is highly involved in substations. The conventional substations are not capable to meet these requirements since they have been built in bulk sizes, increased use of RES plants, and complicated operation requirements. However, novel substations are designed considering high reliability, flexibility, security, interoperability, controllability, and connectivity conditions. They are equipped with interactive control features facilitating ICT interaction and data transmission [48–50].

The IEC 61850 that is the fundamental protocol for legacy SCADA systems is used also for novel substation automation systems (SASs). It is widely used for data transmission along utility network for IED communication, protection and control of relays and circuit breakers, and smart automation systems. IEC61850 has been accepted as a secure and reliable communication technology that is enhanced with industry standard Transmission Control Protocol/Internet Protocol (TCP/IP) networks. The SCADA systems and developed communication technologies are deployed to integrate IED components in smart grid applications. Dynamic condition management of high voltage and coordinator unit between substation and high-voltage control center accomplishes a complete interaction between smart grid and SAS. Hence, a smart substation should acquire and transmit real-time control signals, perform the integration between devices and operation center, and provide smart coordination and management processes as a node connecting transmission and distribution levels of power network. The smart substation is a combination of advanced IEDs, sensor networks, ICTs, and operation software in its complete structure [49, 50].

The SAS requires several control functions such as condition-based maintenance, self-adaption, distributed and centralized control, smart diagnosing, and decision-making to create a secure and reliable management system. The smart substation is enhanced with customized functionalities, smart primary and secondary systems, enhanced interoperability and connectivity, and increased flexibility.

A smart substation and smart metering system have been shown in Fig. 1.13 where the communication layers and protocols are indicated. Legacy IEC 61850 protocol facilitates transmission between conventional distributed metering system and centralized ICT network. The electronic current transformer (ECT) and electronic voltage transformer (EVT) are used for data acquisition at process layer and comprise the process layer network. The merging unit (MU) refers to a system combining digital data inherited from current and voltage transformers. The assembled data transferred to bay layer where the layer network is operated with IEC 61850-9-2 specific communication service mapping (SCSM) [50].

The digital energy meter receives the measurement data at bay layer and realizes the required management operations in the context of AMI infrastructure. The data acquisition terminal is located at station layer that is based on IEC 61850-8-1 standard. The metering option is selected regarding their accuracy rates that non-conventional instrument transformer (NCIT) based on unconventional measurement theory greatly improves the power system reliability and stability with its 0.2% accuracy rate. On the other hand, conventional metering systems with copper transmission provide accuracy around 0.7%, and digitalized metering with fiber-optic transmission provides 0.4% accuracy rate. The accuracy of digitalized metering system increases at small signal measurements [49, 50]. The synchronization times are classified into six groups that are starting from 3 ms to 1 s in smart substation system regarding

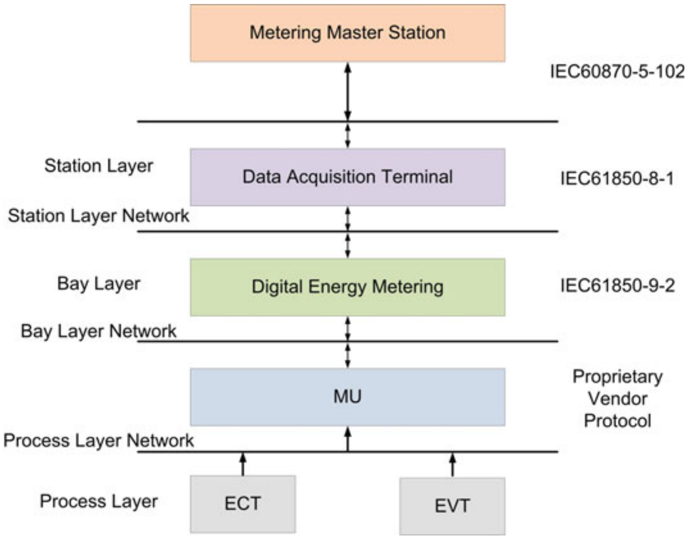

**Fig. 1.13** Smart metering system along smart substation

IEC 61850-5-2 [50]. The smart substation systems are also equipped with protection, control, and security systems in addition to metering systems.

### 1.3.4 Demand-Side Management

One of the most important contributions of smart grid to conventional power network is the penetration of RESs and various alternative energy sources in large share. The intermittent structure of distributed energy resources (DERs) forces energy markets to improve solutions to ensure generation and demand balance between source and load sides. Therefore, two different approaches have been developed up to now that are generation reserve and DSM. The generation reserve approach requires non-dispatchable sources as wind and solar plants that can be supported with controllable source potentials as hydroelectric or CHPs. The controllable sources ensure to back up intermittent wind and solar sources by their large storage and high capacity features [51]. The second approach compensates inconsistency of intermittent DERs by responsive and controllable consumption behaviors. It is related to DSM and DR programs that a confusion considering DSM and DR as same. Although DSM includes DR in addition to efficiency programs, DR does not cover all DSM approaches [25, 51–53].

The DSM plays a vital role to improve efficiency and cost effectivity of power network. DSM systems intend to decrease peak-to-average ratio (PAR) of consumption in the smart grid system. The increased PAR causes increments on source and operation costs and unexpected fluctuations in power network causing outages. The DSM programs encourage customers to use more efficient devices and systems in order to decrease peak load demand and provide incentives to customers to shift their energy consumption to off-peak times [52, 53]. The load shaping methods used in DSM programs include peak clipping, strategic conservation, strategic load growth, flexible load shape, load shifting, and valley filling. These load shaping methods are developed to reduce consumption by directly controlling consumption-side loads [25]. A detailed DSM and integration with smart home system is presented in Chap. 3.

## 1.4 Smart Grid Communication Network Architectures

The communication structure of smart grids can be established by exploiting various protocols based on wired and/or wireless communication methods. One of the most popular wired technologies utilized in smart grid systems is power line communication (PLC) method where the main idea of this communication method is employing existing transmission and distribution power lines as a communication channel. Even though the PLC methods offer the advantage of eliminating the channel installation cost due to the use of current power lines, the aged transmission lines cause several performance problems depending on the varying channel impedances and different types of noises [54, 55]. Typically, data transmission rates of the PLC systems can reach up to the 200 Mbps on the single-phase networks. In addition to wired technologies, there are various wireless communication technologies based on wireless regional area network (WRAN) called IEEE 802.22 standard and wireless personal area network (WPAN) called IEEE 802.15.4 standard [56–62]. In addition, the most common wireless technologies utilized in smart grid systems are Wi-Fi, ZigBee, GSM, and Bluetooth which are preferred to overcome deficiencies of PLC systems at high frequencies.

The communication architecture of the smart grids is characterized by IEEE 2030-2011 standard that is acknowledged as a fundamental guideline to figure out applications and infrastructures of the smart grid systems [61]. This standard provided a general agreement on the smart grid definitions by adopting a logical perspective where the smart grid network is considered as a three-section scheme as can be seen from Fig. 1.14. The first part of this approach which contains HAN, IAN, and BAN is constructed on the consumer domain via private networks. The second network is located at distribution domain that is comprised of WAN including NAN and FAN. These networks are responsible for monitoring and controlling various systems such as AMI, PMU, and remote terminal units [60, 61]. The third network type defined by the standard is called core network that is at the generation and transmission domain. The main components of the core network are broadband communication architectures like LAN, GIS, voice over Internet protocol (VoIP), and virtual private network (VPN) [62–66].

In HAN/BAN/IAN architectures, sensor information acquired from several smart devices located in home, buildings, and industrial areas is collected and is transmitted

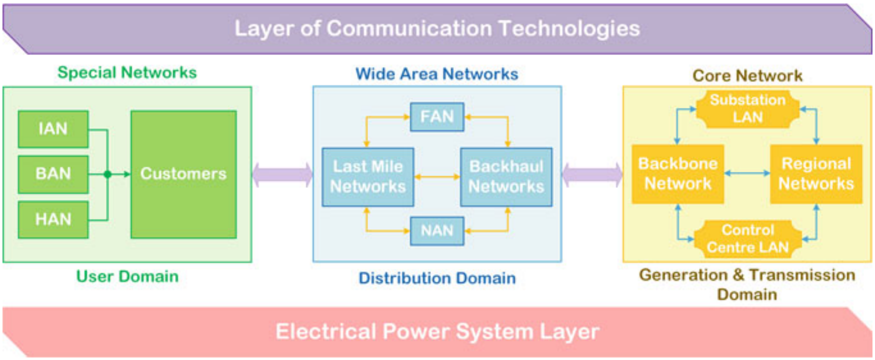

**Fig. 1.14** Smart grid communication architecture defined by IEEE 2030 standard

to management and control center. These architectures are generally considered as premises network. HAN can provide several important features such as controlling electrical appliances depending on the energy consumptions of loads, displaying energy consumption rates for users in home, and supporting prepaid client cards. The smart meters are established in both user sides and industrial plants as a gateway that presents a bridge to transmit information between HANs and NANs. There is no requirement for using high-frequency communications in the applications realized in these networks since all applications are carried out inside of home and buildings. Therefore, these architectures present important advantages for practical implementations such as simplicity, safe communication, low cost, and low power consumption. The wide technologies in these network architectures are Bluetooth, ZigBee, Wi-Fi, PLC-based systems, and Ethernet. The coverage areas of the HANs are typically up to 200 $m^2$, while data rates are between 10 kbps and 100 kbps for per device, and the latency also is not very important for these networks [67, 68].

The main task of the NANs is connection providing from users/customers to data concentrator/substation in which IEDs are generally exploited to gather and manage data from the closest data points. NAN provides to utilize contemporary communication technologies in concentrators and smart meters and transmits energy consumption information and control data according to different requirements. The last node of a NAN can be a smart meter or a data aggregation point (DAP) that gathers data from a few smart meters and conveys collected data to MDMS through a backbone network. The smart meters that can manage miscellaneous smart grid applications such as power quality monitoring, distribution automation, and power outage management can detect amount of energy consumption by acquiring real-time data. The number of smart meters employed in a NAN may change from a few hundred to a few thousand based on the grid topology and utilized communication technology. In addition, the coverage areas of the NANs are typically in the range of square kilometers [67]. Even though the data rates of the NANs are quite lower than those of the WANs, the transmission power level of NANs is very low due to their short-range transmission characteristics. Furthermore, the NAN is also enabled

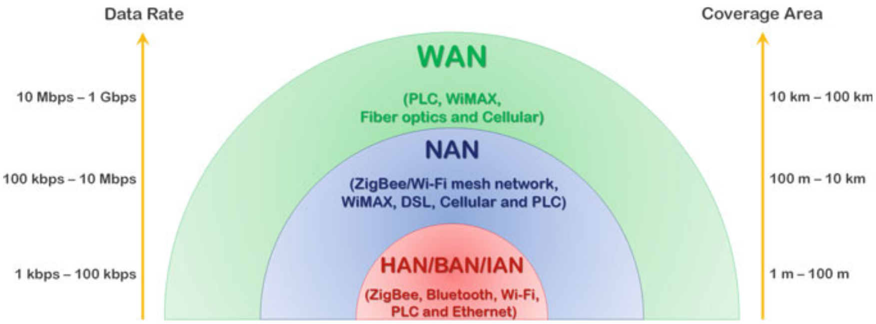

**Fig. 1.15** Comparison of several communication technologies utilized in smart grid networks

in the AMI systems and develops the application ranges of smart grids [61, 68]. The most popular communication technologies employed in NANs are ZigBee and Wi-Fi over mesh networks, PLC, DSL, cellular systems, and WiMAX. Comparison of coverage and data rates for smart grid communication architectures is summarized in Fig. 1.15.

The FAN enables information change between grid control center, distribution substations, and feeders for displaying, controlling, and protection applications. The distribution substations transform high-voltage power into the low-voltage electricity required for homes, offices, and businesses. Moreover, these stations insulate faults from user sides. When a smart grid system is considered, they contain several metering, monitoring, and control systems such as IEDs, PMUs, and RTUs to carry out substation control processes. On the other hand, distribution feeders are composed of transmission lines, tower, and cable poles to present electricity to user facilities. In addition, the feeders behave as the point of common coupling for microgrids. In smart grid systems, many sensor and actuators are superimposed on the distribution feeders for enabling metering and monitoring applications [61]. The communication technologies utilized in smart grid applications are generally characterized based on bandwidth properties as narrowband and broadband. These technologies will be explained in two categories as wired and wireless technologies by the following sections.

The WAN presents a communication platform between utilities and substations. Generally, a typical WAN is composed of power generation plants, distribution stations, and transformer systems, which need real-time measurement and monitoring information to attain a wide-area information. Therefore, the WANs need to sustain a secure backbone communication network with high bandwidth characteristics in order to cope with long-distance information transmission processes. In other words, the WANs create a bridge between energy control centers and data concentrator of each NAN to convey information with high-speed communication [69, 70]. Optical communication is widely utilized among distribution substations and control center because of high capacity and decreased latency advantages of optical communication methods. In addition to optical communication systems, cellular and WiMAX-based systems are also exploited to expand coverage areas of the WANs. For instance, the coverage areas of the WANs may be approximately thousands of square kilometers and they can support up to 10 Mbps data rates for each device [67, 68].

### *1.4.1 Wired Communication Technologies*

The wired communication technologies which are generally employed by service providers in the smart grid applications are responsible for data communication over current transmission lines or additional lines as in fiber-optic and digital subscriber line (DSL) systems [57, 60, 62]. The wired communication systems offer the advantage of stability and robustness against interference. Even though the PLC systems have been commonly employed as a wired communication solution in recent years, there are also alternative technologies employing either fiber cables or telephone lines. Modern digital communication systems can typically reach up to 10 Gbps data rates in DSL technologies, 155 Mbps data rates over coaxial cables, and 160 Gbps data rates over fiber-optic cables [57, 62, 71]. The miscellaneous wired technologies utilized in smart grid systems are listed in Table 1.4 by taking into account several parameters.

The PLC systems need to deal with various challenges because of unforeseen propagation characteristics of power lines. These destructive effects and various interferences are generally originated from electromagnetic systems such as transformers and variable channel impedances [62, 72]. In order to develop robust techniques for eliminating these disruptive effects of power lines, the PLC technologies are analyzed in two categories according to the bandwidth characteristics as narrowband PLC (NB-PLC) and broadband PLC (BB-PLC) systems. In the beginning of the NB-PLC systems, the transmission range was quite small as much as a few Kbps. Later, the effective bandwidths of NB-PLC systems are expanded up to 500 kHz transmission frequencies that can be allowed data rates up to the 500 Kbps in this band. In addition, these systems can be utilized over both low-voltage and high-voltage power lines that may contain more than 150 km lengths of transmission lines. The other one infrastructure covers higher frequencies between 2 MHz and 30 MHz in order to present relatively higher data rates as much as 200 Mbps [62, 64]. The obtained achievements in NB-PLC systems encouraged the advances of BB-PLC systems in smart grid applications that are particularly aimed to be employed for Internet services and HAN applications. The first Internet access and services over power lines were presented at the end of the 1990s in the Europe.

Since the expected performance has not been obtained in Internet access based on PLC systems, researches were focused on the industrial communication and home applications in the beginning of the millennium and several technologies were proposed by various alliances such as HomePlug Powerline Alliance (HomePlug), Universal Powerline Association (UPA), High Definition PLC (HD-PLC) Alliance, and The HomeGrid Forum [64].

**Table 1.4** A detailed comparison list of wired communication technologies utilized in smart grids [1]

| Tech. | Standards | Data Rate | Distance | Network | Advantage | Disadvantage |
|---|---|---|---|---|---|---|
| PLC | •NB-PLC: ISO/IEC 14908-3,14543-3-5, CEA-600.31, IEC61334–3-1, IEC 61334–5 (FSK)<br>• BB-PLC: TIA-1113 (HomePlug 1.0), IEEE 1901, ITU-T G.hn (G.9960/G.9961)<br>• BB-PLC: HomePlug AV/Ext., PHY, HD-PLC | • NB-PLC: 1–10 Kbps for low data rate PHYs, 10–500 Kbps for high data-rate PHYs<br>• BB-PLC: 1–10 Mbps (up to 200 Mbps on very short distance) | • NB-PLC: 150 km or more<br>• BB-PLC: ≈1.5 km | • NB-PLC: NAN, FAN, WAN, large scale<br>• BB-PLC: HAN, BAN, IAN, small scale AMI | • Already constructed wide communication infrastructure<br>• Physical disconnection opportunity according to other networks<br>• Lower operation and maintenance costs | • Higher signal losses and channel interference<br>• Disruptive effects caused by appliances and other electromagnetic interferences<br>• Hard to transmit higher bit rates<br>• Complex routing |
| Fiber optic | • AON (IEEE 802.3ah)<br>• BPON (ITU-T G.983)<br>• GPON (ITU-T G.984)<br>• EPON (IEEE 802.3ah) | • AON:100 Mbps up/down<br>• BPON:155–622 Mbps<br>• GPON: 155–2448 Mbps up, 1.244–2.448 Gbps down<br>• EPON: 1 Gpbs | • AON: up to 10 km<br>• BPON: up to 20-60 km<br>• EPON: up to 20 km | • WAN | • Long-distance communications<br>• Ultra-high bandwidth<br>• Robustness against electromagnetic and radio interference | • Higher installing costs (PONs are lower than AONs<br>• High cost of terminal equipment<br>• Not suitable for upgrading and metering applications |
| DSL | • ITU G.991.1 (HDSL)<br>• ITU G.992.1 (ADSL) , ITU G.992.3 (ADSL2), ITU G.992.5 (ADSL2+)<br>• ITU G.993.1 (VDSL) , ITU G.993.1 (VDSL2) | • ADSL: 8 Mbps down/1.3 Mbps up<br>• ADSL2: 12 Mbps down/3.5 Mbps up<br>• ADSL2+: 24 Mbps down/3.3 Mbps up<br>• VDSL: 52–85 Mbps down/16–85 Mbps up | • ADSL: up to 5 km<br>• ADSL2: up to 7 km<br>• ADSL2+: up to 7 km<br>• VDSL: up to 1.2 km<br>• VDSL2: 300 m–1.5 km | • AMI, NAN, FAN | • Already constructed wide communication infrastructure<br>• Most widely distributed broadband | • Communication operators can charge utilities high prices to use their networks<br>• Not suitable for network backhaul (long distances) |

Over the past decade, important standards such as ITU-T G.hn, IEEE 1901 FFT-OFDM, TIA-1113, and IEEE 1901 Wavelet-OFDM are defined to present technical guides for the PLC applications [64, 73, 74]. After these standards are defined, miscellaneous products are improved that are able to operate at the physical (PHY) layer. The HomePlug 1.0 presented a PLC technology with 14 Mbps data rates, and then HomePlug Turbo provided a system with 85 Mbps data rates. Afterward, HomePlug AV, HD-PLC, and UPA have come up with 200 Mbps data rates. However, none of these systems is compatible with each other.

The most important rival of Wi-Fi systems in HAN is the BB-PLC-based technologies that could not yet become widespread enough in the market. Other wired communication systems are fiber-optic and DSL-based communication systems that ensure higher data rates than the PLC technologies. The main advantages provided optical communication systems are the very large bandwidth in the GHz frequencies and robustness against electromagnetic interferences [62, 64]. Therefore, these important advantages make them appropriate for exploiting over high-voltage power lines. Moreover, a specific cable model called optical power ground wire permits data transmission with high rate in the long-range applications. The DSL technologies exploit conventional telephone lines for performing digital data transmission. Therefore, this method presents the advantage of no additional channel establishing since service providers have already connected to the control centers through telephone lines. The advanced types of DSL technology are asymmetric DSL (ADSL), ADSL2+, and very high-bit-rate DSL (VDSL or VHDSL). The ADSL presents typically 8 Mbps data rate, while the ADSL2 + provides up to 24 Mbps over conventional telephone lines. In addition, the VDSL systems can reach up to 52 Mbps data transmission rates.

### 1.4.2 Wireless Communication Technologies

The wireless communication technologies that are potential candidates to be employed in smart grid systems have been suggested by National Institute of Standards and Technology (NIST). One of the most important key features for smart grid systems to ensure efficiency and stability is demand management that needs to use the most accurate communication technology for expediting the management process. The main selection criteria of proper communication technologies are associated with financial and technological resources [75–77]. Although the wireless technologies offer several advantages such as low installation expenses and wider coverage areas, the main drawback is their sensitivity to bandwidth and inferences. The wireless networks are composed of a couple of mesh networks employing wireless LANs in order to cooperate with electrical devices. The most appropriate AMI frameworks can be created based on NANs and HANs due to their low-cost installation advantage [75, 76]. It is possible to establish communication structure of data management points (DMPs) by exploiting wireless or wired communication technologies where the range between NANs and DMPs may be up to several kilometers. The DMPs have the ability of connecting and managing a large number of smart meters in which a wide coverage can be formed through relaying the DMPs or mesh networking. The contemporary researches in smart grid applications depend on greatly expandable and widespread communication networks that can be simply created by means of WSNs.

In addition, the WSNs need to present a stable infrastructure by reducing latency against demands [76, 77]. For instance, the latency need of OpenSG is typically less than one second for NANs which is more facilitated than that of the commercial broadband communication technologies. HANs which include more narrow coverage areas than NANs as mentioned before are established to achieve energy management and demand planning. On the other hand, HANs generally present latency lower than 5s that is completely lightened when compared with NANs [76]. The most used communication technologies in NANs can be classified as universal mobile telecommunications system (UMTS)/long-term evolution (LTE), worldwide interoperability for microwave access (WiMAX), and IEEE 802.22 standards. Moreover, IEEE 802.11-based Wi-Fi and IEEE 802.15-based WPAN technologies are also exploited in wireless infrastructure of smart grids. The WiMAX that is an implementation of IEEE 802.16 standard is one of the main technologies for providing connectivity among DMPs and smart meters.

This technology employs orthogonal frequency division multiple access (OFDMA) that is the improved version of standard OFDM method for multiple access operations. The multi-user form is achieved by adjusting the subgroups of subcarriers to unique users in this multiple access scheme, which permits simultaneous data transmission coming out of a massive user group [76, 78–80]. This system presents robustness against interferences since the system is constructed based on the idea of OFDM. Therefore, the WiMAX technology remarkably improves the system performance. Although its structure is not complicated as much as cellular communication systems, the WiMAX is not broadly used in smart grid applications. Nevertheless, this case does not restrict its outstanding features due to its DMP cooperation [76]. The several wireless technologies utilized in smart grid systems are listed in Table 1.5 by taking into account several parameters.

A reference standard defined for WPAN is IEEE 802.15.4 that characterizes the PHY layer to present a wireless communication technology for metering and management applications with low power consumption, low cost, and low data rate features. Typically, this WPAN scheme supplies 256 kbps data rates with relatively wide coverage areas up to 1600 m by means of several topologies such as star, mesh, and cluster tree. In each WPAN, a PAN coordinator that is responsible for managing entire network should be situated one in each topology regardless of topology type. Moreover, supplementary routers that provide connection between coordinator and end devices may be contained in mesh and cluster-tree topologies so as to establish multi-hop connections. Various standards on the basis of IEEE 802.15.4 standard which are specified upper layers of communication layers are developed for metering and controlling applications, especially for industrial applications. The most popular ones improved are ZigBee, ISA 100.11a, and WirelessHART. The ZigBee that is one of the most popular technologies among them is accepted in a wide range of application

**Table 1.5** A detailed comparison list of wireless communication technologies utilized in smart grids [1]

| Tech. | Standards | Data Rate | Distance | Network | Advantage | Disadvantage |
|---|---|---|---|---|---|---|
| WPAN | • IEEE 802.15.4<br>• ZigBee, ZigBee Pro, ISA 100.11a | • IEEE 802.15.4: 256 Kbps | • ZigBee: Up to 100 m<br>• ZigBee Pro: Up to 1.6 km | • HAN, BAN, IAN, NAN, FAN, AMI | • Very low power consumption, low-cost deployment<br>• Compatible with IPv6 | • Low bandwidth<br>• Limitations to build large networks |
| Wi-Fi | • IEEE 802.11e<br>• IEEE 802.11n<br>• IEEE 802.11 s<br>• IEEE 802.11p (WAVE) | • IEEE 802.11e/s: up to 54 Mbps<br>• IEEE 802.11n: up to 600 Mbps | • IEEE 802.11e/s/n: up to 300 m<br>• IEEE 802.11p: up to 1 km | • HAN, BAN, IAN, NAN, FAN, AMI | • Low-cost network deployments<br>• Cheaper equipment<br>• High flexibility | • High interference spectrum<br>• Too high power consumption<br>• Simple QoS support |
| WiMAX | • IEEE 802.16<br>• IEEE 802.16j<br>• IEEE 802.16 m | • 802.16: 128 Mbps down/28 Mbps up<br>• 802.16 m: 100 Mbps for mobile, 1 Gbps for fixed users | • IEEE 802.16: 0-10 km<br>• IEEE 802.16 m: 0-5 (opt.), 5-30 acceptable, 30-100 km low | • NAN, FAN, WAN, AMI | • Longer distances than Wi-Fi<br>• A connection-oriented control of the channel bandwidth<br>• More sophisticated QoS than 802.11e. | • Complex network management is<br>• High cost of terminal equipment<br>• Licensed spectrum requirement |
| GSM | • 2G TDM, IS95<br>• 2.5G HSCSD, GPRS<br>• 3G UMTS<br>• 3.5G HSPA, CDMA EVDO<br>• LTE, LTE-A | • 2G: 14.4 kbps<br>• 2.5G: 144 kbps<br>• HSPA: 14.4 Mbps down/5.75 Mbps up<br>• LTE: 326 Mbps down/86 Mbps up<br>• LTE-A: 1Gbps/500Mbps | • HSPA+: 0-5 km<br>• LTE-Advanced: optimum 0-5 km, acceptable 5-30, 30-100 km (reduced performance) | • HAN, BAN, IAN, NAN, FAN, AMI | • Supports millions of devices<br>• Low power consumption of terminal equipment<br>• High flexibility, suitable for different use cases,<br>• Open industry standards | • High prices to use service provider networks<br>• Increased costs since the licensed spectrum |
| Satellite | • LEO<br>• MEO<br>• GEO | • Iridium: 2.4 to 28 Kbps<br>• Inmarsat-B: 9.6 up to 128 Kbps<br>• BGAN: up to 1 Mbps | • 100–6000 km | • WAN, AMI | • Long distance<br>• Highly reliable | • High cost of terminal equipment<br>• High latency |

areas because of its outstanding capabilities on network management [62, 76]. The detailed information for these standards will be presented in the following chapter of this book.

On the other hand, UMTS, LTE, and LTE-Advanced (LTE-A) technologies offer various opportunities for NANs. The most important superiority provided by cellular systems is wider coverage feature when it is compared with other wireless technologies. New cellular technologies have ability to support broader frequency bands and data rates due to rapidly revelation of cellular systems. The UMTS that is a widespread 3G technology supports data communication rates up to 168 Mbps in downlink and 22 Mbps maximum data rate in uplink. The new cellular technologies based on fourth-generation systems are LTE and LTE-A which improves capabilities of UMT systems significantly. They have several differences than UMTS systems such as employing wider bandwidth, better supporting of network schemes, easy interaction between various network structures, and more advanced mobile networking skills.

Another wireless communication alternative is satellite communication systems that permit wireless communication with adjustable bandwidth and latency choices and are especially utilized in areas outside the cellular coverage areas. In previous years, the utilization of satellite communications in power systems was quite restricted and they employed only in SCADA systems since the main drawback of this communication method was quite expensive rather than other wireless technologies. On the other hand, it is expected that the reduced costs of smaller satellite stations may be a potential solution for enabling this communication method in smart grid applications [62, 76]. Orbits are the most important characteristic of satellite communication since they completely influence system performance depending on the bandwidth, latency, and connectivity features. The satellites are situated at orbits having different distances from earth which are called low earth orbits (LEO), medium earth orbit (MEO), and geostationary earth orbits (GEO). While the closest one to earth is the LEO locating between 160 and 2000 km of altitude, the farthest is the GEO locating nearly at 36,000 km. The LEOs are potential solutions for EVs applications due to their permissive structure. The MEO systems generally need additional high-cost hardware for adjusting antenna directions. Unlike the MEO systems, the GEO systems do not require additional hardware owing to their stable terminal structures and are widely exploited in video surveillance and AMI backhaul systems [81].

The cognitive radio (CR) is a new wireless technology which aims to present a novel approach for solving insufficient spectrum issue. The CR is a software-defined radio (SDR)-based technology which can rapidly rearrange its characteristic parameters such as mapping/demapping, error-correcting methods, and data compressing algorithm depending on the varying conditions [82]. As reported by a research related to conventional policies of spectral assignment performed by Federal Communications Commission (FCC), the usage of allocated spectrum changes depending on the time and space from 15 to 85% [83]. However, some sections of the unlicensed band are intensely employed by developing wireless services covering the smart grid applications [84]. Therefore, in order to advance spectrum usage of smart grid communications, it is assumed that the using of CR is a significant technology for dynamically accessing spectrum [85]. There are two different user profiles available in a CR sensor network which are called primary users (PUs) and secondary users (SUs). The PUs are generally called as licensed, authorized, or exclusive users that have capability to exploit frequency band of primary sources. On the other hand, the SUs are defined as CR users and they employ spectrum without a license. It is important to note that the CR users exploit the present spectrum via opportunistic access method that do not interfere with the PUs. The CR users seek the accessible part of the spectrum that is generally defined as TV white space or spectrum gap. Later, the detected accessible channel is exploited by the SUs unless there are no active PUs on the licensed spectrum [86]. Therefore, the CR systems provide an important advantage such as exploiting unlicensed spectrum. Otherwise, this technology encourages the high bandwidths that are needed for transferring massive data containing metering, monitoring, and control information [87].

## 1.5 Conclusion

The researches and technological improvements related to physical structure and components of conventional grid have indicated that the active utilization of communication systems in utility needs to be included to perform metering, monitoring, and controlling processes efficiently. This requirement that has caused development of smart grid concept was crucial for load and source management, efficient metering, and monitoring for all stages of power grids. As a result of these requirements and advancements, the smart grid which has been announced at the beginning of the 2000s is one of the most recent concepts intending to include new features to conventional grids. This new concept is realized to present a data communication environment for transporting various signals that contain important information on the basis of measurement, monitoring, management, and control processes. In addition, this new concept is also associated with utility grid at any section covering generation, transmission, and distribution components. The communication infrastructure of the smart grid that is one of the most important components of this concept needs to ensure data transmission process in a secure, reliable, and efficient way.

This chapter presents essential components of smart grid systems such as sensors networks, smart monitoring and control systems, security requirements, standards and regulations, reliability conditions, wired and wireless communication infrastructures, and quality of services. Firstly, the essential components of smart grid systems are in detail explained by considering smart sensors and sensor networks, phasor measurement unit, smart meters, and wireless sensor networks. Later, the smart grid applications and requirements are analyzed where the smart grid applications are considered in the context of power network systems such as AMI, DR, station and substation automation, and demand-side management systems. Afterward, a featured communication subsection is introduced where the wired and wireless communication technologies commonly exploited in smart grid applications are explained in detail. While the PLC, fiber optics, and DSL technologies are the most important wired communication technologies, Wi-Fi, WiMAX, LTE, LTE-A, satellite, and cognitive radio technologies are the most critical wireless technologies employed in the smart grid systems. Besides, the area networks such as HAN, BAN, IAN, NAN, FAN, and WAN are introduced in a logical way beginning from generation systems to the user side. Each of these components is surveyed and is introduced in terms of challenges, improvements, and contributions comprehensively.

## References

1. Y. Kabalci, A survey on smart metering and smart grid communication. Renew. Sustain. Energy Rev. **57**, 302–318 (2016)
2. E. Kabalci, Y. Kabalci, A wireless metering and monitoring system for solar string inverters. Electr. Power Energy Syst. **96**, 282–295 (2018)
3. E. Kabalci, A smart monitoring infrastructure design for distributed renewable energy systems. Energy Convers. Manag. **90**, 336–346 (2015)
4. E. Kabalci, Y. Kabalci, A measurement and power line communication system design for renewable smart grids. Meas. Sci. Rev. **13**(5), (2013)
5. G.N. Sorebo, R. Echols, *Smart grid security an end-to-end view of security in the new electrical grid* (CRC Press, Boca Raton, FL, 2012)
6. US public law 110–140, energy independence and security act of 2007. pp. 1783–1794 (2007)
7. S.M. Muyeen, S. Rahman (eds.), *Communication, control and security challenges for the smart grid* (The Institution of Engineering and Technology, London, 2017)
8. IEEE Standards Committee, *IEEE guide for smart grid interoperability of energy technology and information technology operation with the electric power system (EPS), end-use applications and loads* (Institute of Electrical and Electronics Engineers, New York, N.Y., 2011)
9. X. Fang, S. Misra, G. Xue, D. Yang, Smart grid-the new and improved power grid: a survey. IEEE Commun. Surv. Tutor. **14**(4), 944–980 (2012)
10. N.S. Nafi, K. Ahmed, M.A. Gregory, M. Datta, A survey of smart grid architectures, applications, benefits and standardization. J. Netw. Comput. Appl. **76**, 23–36 (2016)
11. F. Li et al., Smart transmission grid: vision and framework. IEEE Trans. Smart Grid **1**(2), 168–177 (2010)
12. NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0 (2010)
13. K.C. Budka, J.G. Deshpande, M. Thottan, *Communication Networks for Smart Grids* (Springer, London, London, 2014)
14. S.K. Salman, *Introduction to the Smart Grid: Concept, Technologies and Evolution* (The Institution of Engineering and Technology, London, United Kingdom, 2017)
15. A. Bernieri, L. Ferrigno, M. Laracca, A. Rasile, An AMR-based three-phase current sensor for smart grid applications. IEEE Sens. J. **17**(23), 7704–7712 (2017)
16. M.R. Hossain, A.M.T. Oo, A.B.M.S. Ali, Chapter 2 Smart Grid, in *Smart Grids*, ed. by A.B.M.S. Ali (Springer, London, London, 2013), pp. 23–44
17. E. Kabalci, R. Bayindir, G. Gokkus, Y. Kabalci, in *Renewable Energy Research and Applications (ICRERA), International Conference on, 2015*, Dual DC-DC Converter and Monitoring Interface for Asymmetrical String Inverters, pp. 1580–1585
18. P. Gopakumar, M.J.B. Reddy, D.K. Mohanta, Phasor measurement sensor based angular stability retention system for smart power grids with high penetration of microgrids. IEEE Sens. J. 1–1 (2017)
19. G. Rietveld et al., Measurement infrastructure to support the reliable operation of smart electrical grids. IEEE Trans. Instrum. Meas. 1–1 (2015)
20. E.Y. Song, G.J. FitzPatrick, K.B. Lee, Smart sensors and standard-based interoperability in smart grids. IEEE Sens. J. **17**(23), 7723–7730 (2017)

21. Institute of Electrical and Electronics Engineers and IEEE-SA Standards Board, in *IEEE Standard for Synchrophasor Data Transfer for Power Systems* (Institute of Electrical and Electronics Engineers, New York, 2011)
22. T. Ahmad, Non-technical loss analysis and prevention using smart meters. Renew. Sustain. Energy Rev. **72**, 573–589 (2017)
23. B. Yildiz, J.I. Bilbao, J. Dore, A.B. Sproul, Recent advances in the analysis of residential electricity consumption and applications of smart meter data. Appl. Energy **208**, 402–427 (2017)
24. S. Erlinghagen, B. Lichtensteiger, J. Markard, Smart meter communication standards in Europe—a comparison. Renew. Sustain. Energy Rev. **43**, 1249–1262 (2015)
25. S. Kakran, S. Chanana, Smart operations of smart grids integrated with distributed generation: a review. Renew. Sustain. Energy Rev. **81**, 524–535 (2018)
26. C. Alcaraz, J. Lopez, A security analysis for wireless sensor mesh networks in highly critical systems. IEEE Trans. Syst. Man Cybern. Part C Appl. Rev. **40**(4), 419–428 (2010)
27. M.M. Hasan, H.T. Mouftah, Optimal trust system placement in smart grid SCADA networks. IEEE Access **4**, 2907–2919 (2016)
28. A. Sajid, H. Abbas, K. Saleem, Cloud-assisted iot-based SCADA systems security: a review of the state of the art and future challenges. IEEE Access **4**, 1375–1384 (2016)
29. E. Fadel et al., A survey on wireless sensor networks for smart grid. Comput. Commun. **71**, 22–33 (2015)
30. F. Wang, J. Liu, Networked wireless sensor data collection: issues, challenges, and approaches. IEEE Commun. Surv. Tutor. **13**(4), 673–687 (2011)
31. N.K. Suryadevara, S.C. Mukhopadhyay, S.D.T. Kelly, S.P.S. Gill, WSN-Based smart sensors and actuator for power management in intelligent buildings. IEEEASME Trans. Mechatron. **20**(2), 564–571 (2015)
32. N.A. Pantazis, S.A. Nikolidakis, D.D. Vergados, Energy-efficient routing protocols in wireless sensor networks: a survey. IEEE Commun. Surv. Tutor. **15**(2), 551–591 (2013)
33. I. Butun, S.D. Morgera, R. Sankar, A survey of intrusion detection systems in wireless sensor networks. IEEE Commun. Surv. Tutor. **16**(1), 266–282 (2014)
34. H. Sun (ed.), *Smarter Energy: From Smart Metering to the Smart Grid* (The Institution of Engineering and Technology, London, 2016)
35. Y. Kabalci, E. Kabalci, Modeling and analysis of a smart grid monitoring system for renewable energy sources. Sol. Energy **153**, 262–275 (2017)
36. Y. Kabalci, E. Kabalci, R. Canbaz, A. Calpbinici, Design and implementation of a solar plant and irrigation system with remote monitoring and remote control infrastructures. Sol. Energy **139**, 506–517 (2016)
37. Y. Kabalci, E. Kabalci, Design and implementation of wireless energy monitoring system for smart grids. Gazi Univ. J. Sci. Part C **5**(2), 137–145 (2017)
38. E. Kabalci, Y. Kabalci, in *2017 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE),* Remote Monitoring System Design for Photovoltaic Panels (2017), pp. 888–891
39. Y. Kabalci, E. Kabalci, in *2016 8th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*, A Low Cost Smart Metering System Design for Smart Grid Applications (2016), pp. 1–6
40. Z. Li, F. Yang, S. Mohagheghi, Z. Wang, J.C. Tournier, Y. Wang, Toward smart distribution management by integrating advanced metering infrastructure. Electr. Power Syst. Res. **105**, 51–56 (2013)
41. J. Zhou, R. Qingyang Hu, Y. Qian, Scalable distributed communication architectures to support advanced metering infrastructure in smart grid. IEEE Trans. Parallel Distrib. Syst. **23**(9), 1632–1642 (2012)
42. A.F.A. Aziz, S.N. Khalid, M.W. Mustafa, H. Shareef, G. Aliyu, Artificial intelligent meter development based on advanced metering infrastructure technology. Renew. Sustain. Energy Rev. **27**, 191–197 (2013)

43. R. Rashed Mohassel, A. Fung, F. Mohammadi, K. Raahemifar, A survey on advanced metering infrastructure. Int. J. Electr. Power Energy Syst. **63**, 473–484 (2014)
44. M. Manbachi, H. Farhangi, A. Palizban, S. Arzanpour, Smart grid adaptive volt-VAR optimization: challenges for sustainable future grids. Sustain. Cities Soc. **28**, 242–255 (2017)
45. N. Good, K.A. Ellis, P. Mancarella, Review and classification of barriers and enablers of demand response in the smart grid. Renew. Sustain. Energy Rev. **72**, 57–72 (2017)
46. H.T. Haider, O.H. See, W. Elmenreich, A review of residential demand response of smart grid. Renew. Sustain. Energy Rev. **59**, 166–178 (2016)
47. P. Siano, Demand response and smart grids—a survey. Renew. Sustain. Energy Rev. **30**, 461–478 (2014)
48. A. Angioni et al., Design and implementation of a substation automation unit. IEEE Trans. Power Deliv. **32**(2), 1133–1142 (2017)
49. B. Vaidya, D. Makrakis, H.T. Mouftah, Authentication and authorization mechanisms for substation automation in smart grid network. IEEE Netw. **27**(1), 5–11 (2013)
50. Q. Huang, S. Jing, J. Li, D. Cai, J. Wu, W. Zhen, Smart substation: state of the art and future development. IEEE Trans. Power Deliv. **32**(2), 1098–1105 (2017)
51. M. Alizadeh, X. Li, Z. Wang, A. Scaglione, R. Melton, Demand-Side management in the smart grid: information processing for the power switch. IEEE Signal Process. Mag. **29**(5), 55–67 (2012)
52. F. Ye, Y. Qian, R.Q. Hu, A real-time information based demand-side management system in smart grid. IEEE Trans. Parallel Distrib. Syst. **27**(2), 329–339 (2016)
53. L. Song, Y. Xiao, M. van der Schaar, Demand side management in smart grids using a repeated game framework. IEEE J. Sel. Areas Commun. **32**(7), 1412–1424 (2014)
54. E. Kabalci, Y. Kabalci, I. Develi, Modelling and analysis of a power line communication system with QPSK modem for renewable smart grids. Int. J. Electr. Power Energy Syst. **34**(1), 19–28 (2012)
55. E. Yaacoub, A. Abu-Dayya, Automatic meter reading in the smart grid using contention based random access over the free cellular spectrum. Comput. Netw. **59**, 171–183 (2014)
56. Y. Yan, Y. Qian, H. Sharif, D. Tipper, A survey on smart grid communication infrastructures: motivations, requirements and challenges. IEEE Commun. Surv. Tutor. **15**(1), 5–20 (2013)
57. W. Wang, Y. Xu, M. Khanna, A survey on the communication architectures in smart grid. Comput. Netw. **55**(15), 3604–3629 (2011)
58. A. Usman, S.H. Shami, Evolution of communication technologies for smart grid applications. Renew. Sustain. Energy Rev. **19**, 191–199 (2013)
59. X. Lu, W. Wang, J. Ma, An empirical study of communication infrastructures towards the smart grid: design, implementation, and evaluation. IEEE Trans. Smart Grid **4**(1), 170–183 (2013)
60. M. Kuzlu, M. Pipattanasomporn, S. Rahman, Communication network requirements for major smart grid applications in HAN, NAN and WAN. Comput. Netw. **67**, 74–88 (2014)
61. R.H. Khan, J.Y. Khan, A comprehensive review of the application characteristics and traffic requirements of a smart grid communications network. Comput. Netw. **57**(3), 825–845 (2013)
62. E. Ancillotti, R. Bruno, M. Conti, The role of communication systems in smart grids: Architectures, technical solutions and research challenges. Comput. Commun. **36**(17), 1665–1697 (2013)
63. W. Li, X. Zhang, Simulation of the smart grid communications: challenges, techniques, and future trends. Comput. Electr. Eng. **40**(1), 270–288 (2014)
64. S. Galli, A. Scaglione, Z. Wang, For the grid and through the grid: the role of power line communications in the smart grid. Proc. IEEE **99**(6), 998–1027 (2011)
65. T. Khalifa, K. Naik, A. Nayak, A survey of communication protocols for automatic meter reading applications. IEEE Commun. Surv. Tutor. **13**(2), 168–182 (2011)
66. Z. Fan et al., Smart grid communications: overview of research challenges, solutions, and standardization activities. IEEE Commun. Surv. Tutor. **15**(1), 21–38 (2013)
67. Q.-D. Ho, Y. Gao, T. Le-Ngoc, Challenges and research opportunities in wireless communication networks for smart grid. IEEE Wirel. Commun. **20**(3), 89–95 (2013)

68. S. Xu, Y. Qian, R.Q. Hu, On reliability of smart grid neighborhood area networks. IEEE Access **3**, 2352–2365 (2015)
69. A. Keyhani, A. Chatterjee, Automatic generation control structure for smart power grids. IEEE Trans. Smart Grid **3**(3), 1310–1316 (2012)
70. M.H. Variani, K. Tomsovic, Distributed automatic generation control using flatness-based approach for high penetration of wind generation. IEEE Trans. Power Syst. **28**(3), 3002–3009 (2013)
71. S. Liu, X.P. Liu, A. El Saddik, Modeling and distributed gain scheduling strategy for load frequency control in smart grids with communication topology changes. ISA Trans. **53**(2), 454–461 (2014)
72. N. Saputro, K. Akkaya, S. Uludag, A survey of routing protocols for smart grid communications. Comput. Netw. **56**(11), 2742–2771 (2012)
73. M.M. Rahman, C.S. Hong, S. Lee, J. Lee, M.A. Razzaque, J.H. Kim, Medium access control for power line communications: an overview of the IEEE 1901 and ITU-T G.hn standards. IEEE Commun. Mag. **49**(6), 183–191 (2011)
74. J. Brown, J.Y. Khan, Key performance aspects of an LTE FDD based smart grid communications network. Comput. Commun. **36**(5), 551–561 (2013)
75. Y. Xu, W. Wang, Wireless mesh network in smart grid: modeling and analysis for time critical communications. IEEE Trans. Wirel. Commun. **12**(7), 3360–3371 (2013)
76. Z. Zhu, S. Lambotharan, W.H. Chin, Z. Fan, Overview of demand management in smart grid and enabling wireless communication technologies. IEEE Wirel. Commun. **19**(3), 48–56 (2012)
77. R. Ma, H.-H. Chen, Y.-R. Huang, W. Meng, Smart grid communication: its challenges and opportunities. IEEE Trans. Smart Grid **4**(1), 36–46 (2013)
78. H. Wang, Y. Qian, H. Sharif, Multimedia communications over cognitive radio networks for smart grid applications. IEEE Wirel. Commun. **20**(4), 125–132 (2013)
79. D. Niyato, P. Wang, Cooperative transmission for meter data collection in smart grid. IEEE Commun. Mag. **50**(4), 90–97 (2012)
80. P. Kulkarni, S. Gormus, Z. Fan, B. Motz, A mesh-radio-based solution for smart metering networks. IEEE Commun. Mag. **50**(7), 86–95 (2012)
81. A. Meloni, L. Atzori, The role of satellite communications in the smart grid. IEEE Wirel. Commun. **24**(2), 50–56 (2017)
82. S. Alam, M.F. Sohail, S.A. Ghauri, I.M. Qureshi, N. Aqdas, Cognitive radio based smart grid communication network. Renew. Sustain. Energy Rev. **72**, 535–548 (2017)
83. Federal Communications Commission, Spectrum policy task force report, Washington, USA, ET Docket No. 02–135 (2002)
84. I.F. Akyildiz, W.-Y. Lee, M.C. Vuran, S. Mohanty, Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey. Comput. Netw. **50**(13), 2127–2159 (2006)
85. T. Le Nghia, W.-L. Chin, H.-H. Chen, Standardization and security for smart grid communications based on cognitive radio technologies—a comprehensive survey. IEEE Commun. Surv. Tutor. **19**(1), 423–445 (2017)
86. E.U. Ogbodo, D. Dorrell, A.M. Abu-Mahfouz, Cognitive radio based sensor network in smart grid: architectures, applications and communication technologies. IEEE Access **5**, 19084–19098 (2017)
87. J. Huang, H. Wang, Y. Qian, C. Wang, Priority-Based traffic scheduling and utility optimization for cognitive radio communication infrastructure-based smart grid. IEEE Trans. Smart Grid **4**(1), 78–86 (2013)