Chapter 3
Technical Challenges and Enhancements in Smart Grid Applications

Ersan Kabalci

Abstract This chapter deals with novel technologies in terms of power electronics, power converters, information and communication technologies (ICTs), energy storage systems (ESSs), electric vehicles (EVs), and microgeneration systems in the context of smart grid applications. Although the smart grid was a concept defining ICT-enabled conventional grid at the beginning, it has now improved its own infrastructure with particularly tailored applications and technologies. During this improvement stage; researchers, engineers, and technology improving alliances have overcome many technical challenges. This chapter presents a number of innovative solutions enhanced against challenges met during improvement era. They have been introduced in terms of power electronics and power converters, integration of communication systems to power devices; improved microgrid, generation and transmission systems, the demand side management (DSM) policies, smart home management systems, ESSs and EVs. The surveyed device topologies and technologies are particularly selected in order to present a set of recent application in smart grid infrastructure. Therefore, widely known devices, systems, and methods that can be found in any regular textbook are not considered in this section.

Keywords Demand side management · Demand response · Distributed generation · Energy management system · Phasor measurement unit · Supervisory control and data acquisition system

3.1 Introduction

Three layers of operation that is generation, transmission, and distribution comprise the conventional power system. On the other hand, the modern grid structure presents

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several improvements at each layer. The generation cycle was being performed by using fossil-based fuels such as crude oil, coal, and natural gas. However, recent increases on fuel prices and limitations on reaching rich fossil fuel reserves directed governments and investors to search alternative sources that are critical on decreasing generation and operation costs, dependency to foreign sources, and increasing the use of geographically available natural sources such as wind, solar, and tidal power. The improvements in generation policies and incentives for individual generation have got started a new era for existing power system. The unidirectional power flow that is realized from generation system operators (GSOs) to consumer is enhanced to provide bidirectional power flow with distributed generation (DG) and microgrid (MG) implementations since a few decades. The regulations on integration of renewable energy sources (RES) and DG incentives were milestones of this improvement.

The transmission and distribution systems have also experienced a number of enhancements due to these improvements. The transmission and distribution systems and substations require voltage conversions from high voltage to medium voltage (MV) and low voltage (LV) in the context of power flow. The main components of a power system obviously involved severe and dedicated control systems for monitoring voltage magnitudes, phase angles, frequency, and several other power parameters. The conventional grid has been strengthened with traditional control systems such as supervisory control and data acquisition (SCADA), phasor measurement systems (PMUs), and energy management systems (EMSs). However, the recent grid system that is named as smart grid (SG) provides bidirectional data flow on communication systems in addition to bidirectional power flow. Thus, conventional communication and control systems have been extensively improved as well as power system infrastructures. The most recent control mechanisms are based on widespread communication protocols and wide area network-type data management systems. The main novelty that is provided by SG is enhancing bidirectional energy and data flow between GSO and consumers. The extended control and management infrastructures enable SG to react against sudden changes by taking action to sustain generation, transmission, distribution, and consumption layers to operate individually or jointly. Sensor networks and agent-based monitoring and control infrastructure improve the decision-making and operating capability that provides actual data flow without any intermittency [1–5].

The SG that is improved by transforming the conventional grid with communication systems, namely DG, RES, and MG integration still faces with several problems. A complete bidirectional communication system could not be installed at each section of conventional grid due to several line deficiencies. Moreover, most of the power plants and utilities are not capable of instant monitoring and measuring the energy consumption on consumer side, and even it is not possible to improve such a system without modernizing the transmission and distribution infrastructure at all. The reliability, efficiency, flexibility, and resiliency of SG should be taken into consideration besides its communication and energy aspects [1, 2, 5]. The objectives of SG are addressed to enable intelligent services for monitoring, control, data transmission, and self-healing features in addition to conventional grid operations. Therefore, a SG infrastructure is expected to allow secure, stable, reliable, and sustainable energy and

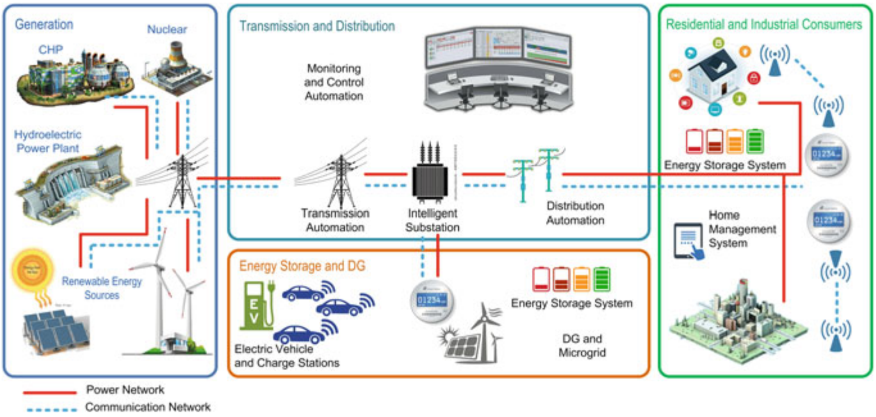

Fig. 3.1 Smart grid infrastructure with its components

communication environments by facilitating integration of RESs and MG sources to utility grid. The smart home management systems and smart appliance support on the residential and industrial consumer side are also involved in SG infrastructure [3]. The most recent SG researches include automatic generation control (AGC) , frequency control in the context of rate of change of frequency (RoCoF) monitoring, phasor measurement units (PMUs), demand side management (DSM), demand response (DR) control, smart metering in terms of advanced metering interface (AMI) , smart protection for generators and substations, and eventually information and communication technologies (ICT) [5]. The challenges and enhancements of SG are classified into three categories in terms of infrastructure, management and protection where the applications are addressed to power electronics, generation and distribution systems with particular source and load types, and ICT improvements in communication and data management. Although it is possible to increase classification type, the overall progress of SG is covered by challenges and enhancements on power and communication systems.

A complete diagram of a typical SG infrastructure is illustrated in Fig. 3.1 where the layers are depicted as generation, transmission and distribution, energy storage and DG, and residential and industrial consumers. The generation layer includes conventional sources such as CHP, nuclear plants, hydroelectric plants, and RESs such as wind turbines and solar power plants. The power network is depicted with red line that already exists and comprises the conventional grid while SG is improved due to communication network, which is shown in dotted blue line.

In addition to generation layer, the communication network is utilized at each layer where it is a critical component in transmission and distribution layers to monitor and to control the station automation. The conventional SCADA system is replaced with wired and wireless communication network that comprises AMI. The monitoring and control center provides required measurement data of transmission system, intelligent substation interaction, and distribution automation. The intelligent substations enable utilization of ESSs, DG systems, and microgrid sources. The EVs and charge stations are accepted as particular ESSs due to charge and discharge cycles that are defined with vehicle-to-grid (V2G) terms. The contributions of such systems allow bidirectional power flow on conventional power network. The residential and industrial consumers may have their own ESSs and MG sources interacting with utility grid to perform SG operations. Besides, the smart meters, home management system, remote automation systems commutate bidirectional power and data flow on grid infrastructure.

The SG infrastructure that is illustrated with the aforementioned components demands reliable, efficient, and secure management of power and data. The technical challenges and enhancements of SG applications are handled in the following subheadings that are presenting the contribution of power electronics, enhancements in generation, transmission, distribution and microgrid systems, improvements on ESSs, EVs, and ICT systems. Each of these components is reviewed and is presented in terms of challenges, improvements, and contributions in the following subsections.

3.2 Contributions of Recent Power Electronics to Smart Grid

The SG infrastructure is analyzed by classifying into three subsystems that are generation, transmission, and distribution. The energy conversion and communication infrastructures along these subsystems are integrated with power electronics devices and conversion systems including DC–DC converters, inverters, high-voltage direct current (HVDC), high-voltage alternative current (HVAC), flexible alternative current transmission systems (FACTS), adjustable speed drives (ASDs), charge controllers of ESSs, and uninterruptible power supplies (UPSs). Regardless of power electronics type, any of these systems are involved with control infrastructures and measurement interfaces that are managed by sensor networks, microprocessors, intelligent electronic devices (IEDs), smart transformers, prediction and self-healing algorithms, and hierarchical controllers. The power electronics along with SG can be assumed as an everlasting research area in terms of communication-enabled devices and systems. The contributions of power electronics to SG applications are summarized in device topologies, prominent control algorithms, energy efficiency, and smart management systems that are based on smart metering interfaces in the remainder. It should be noted that smart metering interfaces are not only addressed for metering energy consumption but also for detecting particular magnitudes of a power electronic system in terms of voltage, current, frequency, and phasors.

The large penetration of RESs to conventional grid has improved involved power electronics control systems particularly for solar, wind, fuel cell, tidal, and similar energy sources. Thus, several featured controllers such as maximum power point tracking (MPPT), active and reactive power controllers, computational algorithms, agent-based communication infrastructures, and dedicated data management systems have been improved to facilitate the integration of power electronics and communication systems[3, 5]. The remainder of this section presents some selected applications of power electronics that are featured for SG applications.

3.2.1 Power Converters and Inverters

The power converters and inverters are involved to interface RESs and DG sources with utility grid. The conventional isolated and non-isolated DC converters are utilized in the SG applications as well. However, the RES control requires intelligent algorithms such as MPPT, resonant control, and computational control algorithms in order to manage power conversion and to increase the efficiency. Moreover, DC converters are equipped with high-frequency and high-power features to deal with large DC power plants and grid connection. The inverters are also improved to interface large penetration of DG sources and provide several modern communication features to enable SG interconnection where monitoring and control requirements are met. The most recent inverter topologies that enforce DG and SG integration are string inverters and microinverters in addition to legacy central and multilevel inverter (MLI) topologies. A large number of inverter topologies and control methods have been surveyed in [6] where diode clamped, flying capacitor, and cascaded H-bridge topologies are prominent. Although these topologies have been widely used for several years, there are some novel topologies that have been implemented.

There are numerous power electronic applications found in the literature that research islanding control [7], resonant power converters for RES integration [8, 9], power quality monitoring [10], multiple DC converters [11, 12], and power converters operated in rural areas [13]. The selected power electronics applications are featured with their wired and wireless communication systems that are improved in the context of SG applications. A general block diagram of a power electronics system with communication network is illustrated in Fig. 3.2, while the block diagram of a solar string inverter located in PV plant is shown in Fig. 3.3 with DC power converters, inverter, measurement section, and monitoring infrastructure [11, 12]. These types of inverters are widely used in LV and MV integration of RESs with communication capabilities. The increased number of MPPT algorithms enables the use of multiple input terminals that increases the total power handled by inverter. Therefore, novel DC converter topologies are improved to enable use of multiple MPPT algorithms and increased DC input power rates. The inverter topologies following DC converter section have been improved as well.

However, the contributions of power electronics to the SG vision is not limited with converter and inverter topologies. The essential power electronics are covered by several other technologies such as solid-state transformers (SST), intelligent tap changing transformers, medium and high voltage interface components, distributed energy storage devices (DESD), distributed RES. The SG vision is being performed by some renowned initiative projects such as Future Renewable Electric Energy Delivery and Management (FREEDM) System that is demonstrated and sustained

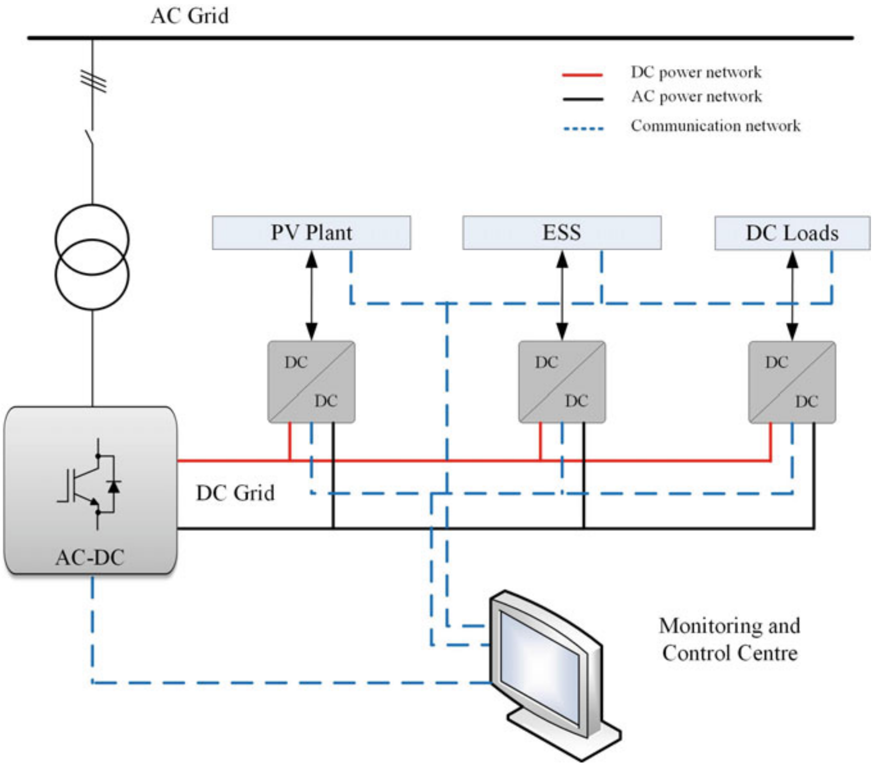

Fig. 3.2 Block diagram of a power network with DG and communication systems

as energy internet by North Carolina University [14]. The FREEDM and similar systems target getting the SG researches to focus on advanced power electronics and ICT by allowing easy integration of any DESD and DGs, load management with intelligent control, interfacing load through solid-state devices, presenting protection devices known as fault isolation device (FID), and improving power quality [14].

In another approach, intelligent power conversion systems named power electronic building blocks (PEBB) and mechanical building blocks (MBBs) are assumed to integrate ESSs, loads, and DG sources to perform SG envision [15]. The PEBB shown in Fig. 3.4 is comprised of power converters and can interact with any communication network to provide efficient and reliable control infrastructure. The security of PEBBs is a challenging issue for SG applications in the context of power electronics. PEBBs provide numerous circuit topologies including AC–DC–DC, AC–DC–AC, AC–DC, and DC–AC conversion devices that are widely used in generation, transmission, and distribution layers. Thus, PEBBs allow comprising an interface along generators, RESs, ESSs, and loads where some mechanical building blocks (MBBs) and mechanical electrical (ME) interfaces may be required for particular integration [15].

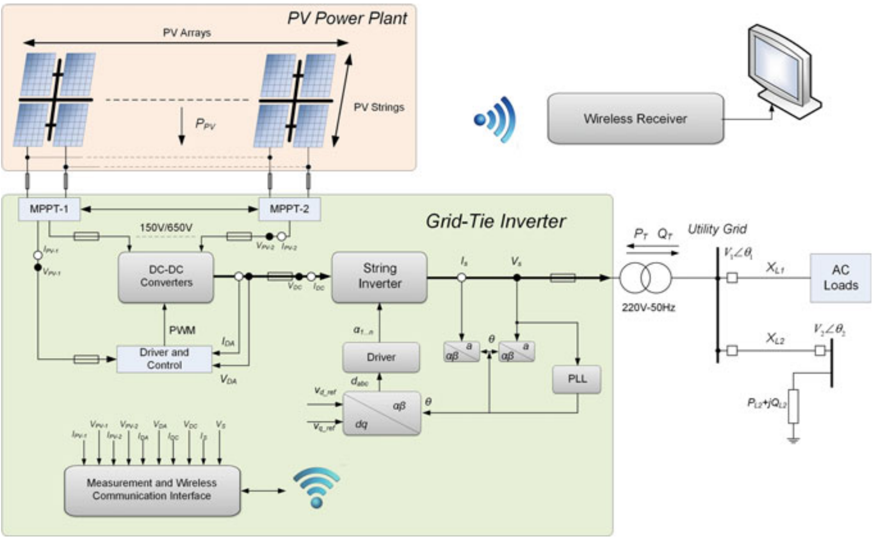

Fig. 3.3 Block diagram of a string inverter with remote monitoring interface

The improvements in power electronics devices and circuit types replace well-known core and copper-based legacy transformer with SST that is an emerging technology enhancing the recent intelligent universal transformers (IUT). Although the SST term implies a transformer, a solid-state switching device transforms voltage and current levels with a few stages. Therefore, it facilitates to integrate distributed energy resources (DERs), DESD, and intelligent loads to utility grid. It provides better power efficiency, less size and volume, and higher power density compared to physical line frequency or high-frequency transformers. Several SST and IUT topologies for AC–DC–DC–DC, AC–AC–AC, or AC–DC–DC–AC conversions have been introduced in the literature [14, 16–19]. A rectifier, a DC–DC converter, and an inverter comprise the three-stage SST to provide AC–DC–AC conversion. It is one of the most widely researched topologies among others since it enables power factor correction (PFC), DC bus regulation at DC–DC converter stage, and reactive power compensation at inverter section. The power converter structure of three-stage SST provides RES and ESS interface, while the regulated DC–DC converter performs galvanic isolation at high-frequency switching. Moreover, the DC–DC converter stage is designed to constitute bidirectional conversion that increases overall efficiency and reliability. This topology eliminates particular disadvantages of DC converters and single-stage inverters by interfacing source and load sides over isolated low- and high-frequency stages. The preliminary SST researches have been implemented considering MV input and three-level neutral point clamped (NPC) converter is used for AC–DC conversion. Electric Power Research Institute (EPRI), ABB, UNIFLEX, and FREEDM have replaced NPC topology with diode clamped and cascaded H-bridge MLI topologies at the input of SST that stands for primary winding of legacy

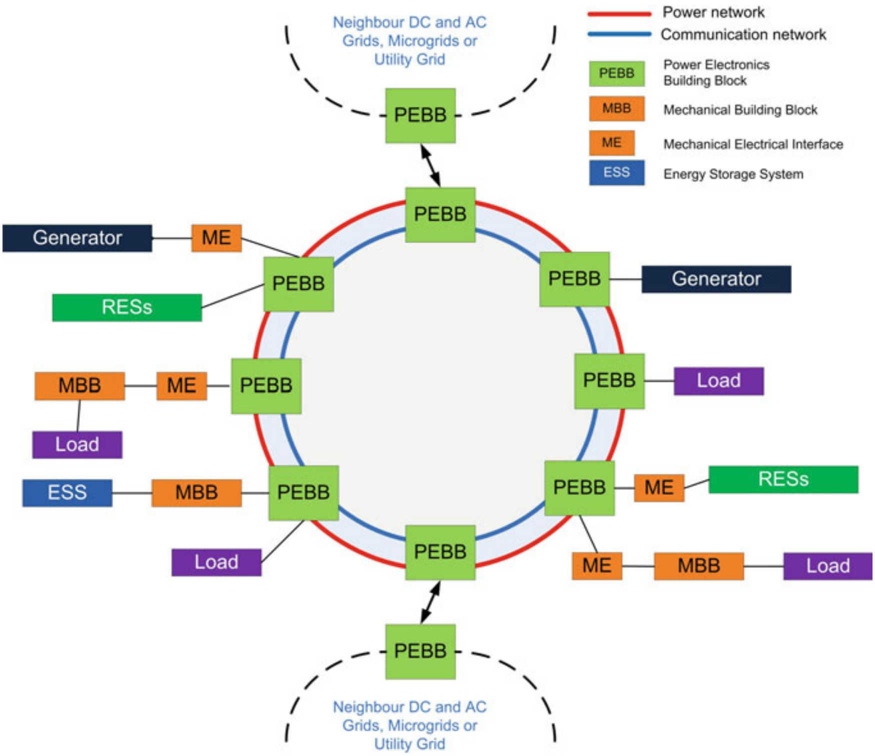

Fig. 3.4 Schematic diagram of electrical and mechanical systems integration along SG envision

transformer. The DC–DC conversion stage and inverter at the output differ regarding selected topology and designers priorities. FREEDM have improved three generations of SST for SG applications that the first generation (Gen-I) was comprised of silicon-insulated gate bipolar transistors (Si IGBT), 2nd and third generations (Gen-II and Gen-III) with silicon carbide Mosfets (SiC MOSFETs). The Gen-I and Gen-II SST of FREEDM model have been designed in three-stage power conversion block as shown in Figs. 3.5 and 3.6 where Gen-I interfaces single-phase 7.2 kV voltage, while Gen-II is capable to interface 20 kV single-phase input voltage. The first-generation SST of FREEDM uses Si IBGTs rated at 6.5 kV and 25A, comprised of three stages as AC–DC rectifier and DC–DC converter are followed by a full-bridge inverter to supply 240 V/120 V single-phase output voltages.

The DC–DC converter of Gen-I SST is built with a dual active bridge topology where converter is bidirectional and includes a high-frequency transformer converting 3.8 kV input voltage to 400 V DC bus voltage. Thus, DC output voltages at various levels can be obtained at the output of SST in addition to inverter outputs. Although the three-stage structure of second-generation SST is similar to Gen-I, it differs in terms of single-level AC input, dual half-bridge DC converter, and switch-

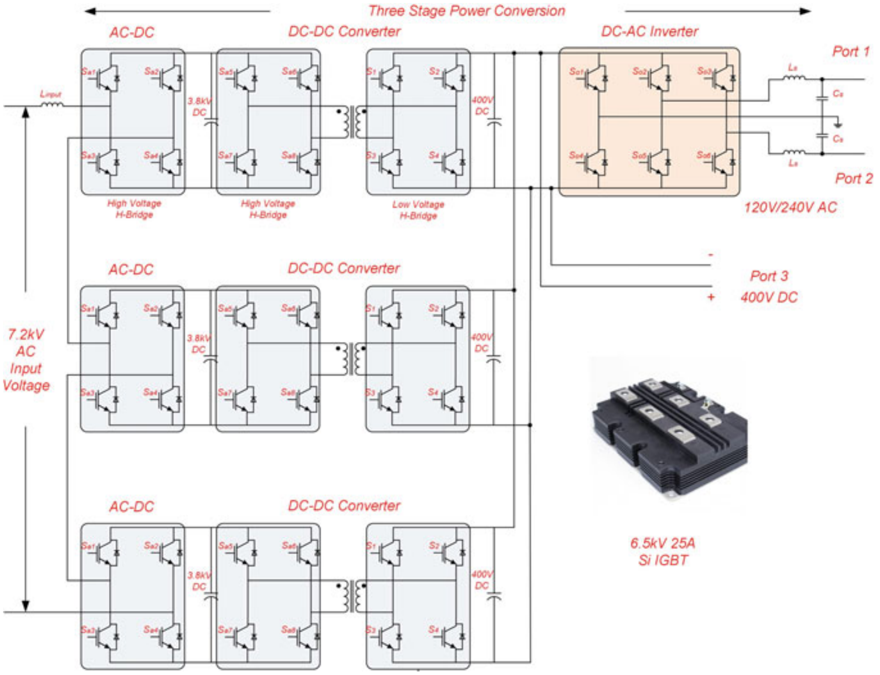

Fig. 3.5 Gen-I SST of FREEDM with 6.5 kV-25A Si IGBT based topology

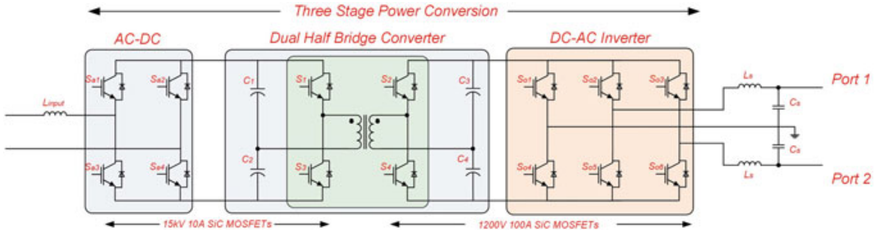

Fig. 3.6 Gen-II three-stage SST of FREEDM with 15 kV-10A SiC Mosfet

ing devices of SiC MOSFETs as illustrated in Fig. 3.6. The new generation of SiC devices improves input voltage range of Gen-II SST up to 20 kV that allows facilitating to handle high power with decreased number of switches.

The modular rectifier of Gen-II SST is capable to perform AC–DC conversion by using four MOSFETs in contrast to multilevel input topology of Gen-I SST and decreased DC–DC converter topology to dual half-bridge instead of dual active bridge of previous topology. 15 kV 10A SiC MOSFETs drive the primary of high-power high-frequency transformer, while 1200 V 100A SiC MOSFETs interface the secondary that supplies full-bridge inverter to generate 240 V/120 V single-phase output voltage. The Gen-III SST that is shown in Fig. 3.7 is implemented by replacing

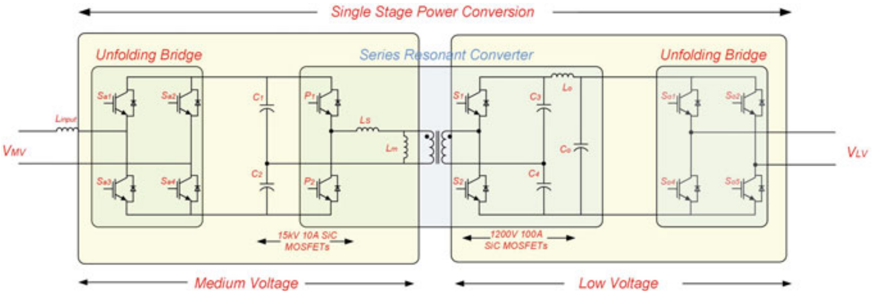

Fig. 3.7 Gen-III single-stage SST of FREEDM with 15 kV-10A SiC Mosfet

dual half bridge of Gen-II SST with a series resonant converter. Although the input and output switching devices are similar in both topologies, efficiency is increased up to 97% [14, 20]. The breakdown voltage of Si IGBT was around 6 kV, and it had maximum switching frequency around one kHz for this voltage level. However, SiC MOSFETs can be operated at 8 kHz switching frequency under 15 kV input voltage in hard switching circuits while the resonant circuits increase switching frequency up to 100 kHz. Thus, the efficiency of series resonant converter in Gen-III SST is reaches up to 98.2% while dual half-bridge converter in Gen-II SST provides 97.4% efficiency. In addition to efficiency, Gen-III SST provides several SG applications such as low-voltage right through (LVRT), load harmonic mitigation, utility grid enhancement by injecting reactive power, regenerative and bidirectional power flow, and DC microgrid support [20].

The gallium nitride (GaN) is a wide energy gap material like SiC that provides higher blocking voltage and higher switching frequency. The performance of DC–DC converter has been extended by improving series resonant converter types as CLLC in addition to LLC topology. Thus, switching and conduction losses have been severely decreased; voltage and frequency limits have been extended up to 15 kW and 500 kHz, respectively [21]. The semiconductor improvements provided critical contributions to power electronic devices used in SG applications. Moreover, novel device topologies have been improved due to these high-voltage high-frequency operating capabilities. On the other hand, communication system has been integrated with legacy and novel power devices.

3.2.2 Communication-Enabled Power Converters

The improvements in power electronics are not only seen in semiconductors and devices but also in remote monitoring and communication methods. The DER, DR, SG control, and cyber security issues have been extensively researched since last decade. The MGs and conventional generation systems have been enhanced with autonomous operation and remote control features in the context of the recent researches. The RES plants are widely installed in rural areas where the utility grid is not available or is far away to perform interconnection. Besides, innovative solution is required to interconnect most recent generation and transmission systems to degraded traditional grid. Therefore, increased number of quality measurements is carried out on generation, interconnection, transmission, and distribution phases of any DG plants to utility grid. The measured and monitored quality parameters are voltage, current, phase, frequency, and power rates regarding the system features. The power electronic devices of a system that is used by energy supplier should provide power at stable frequency, voltage, and other magnitudes. In addition to fundamental magnitudes, the harmonic contents, power factor, waveform distortions, and other deficiencies should be instantly tracked and be solved to improve power quality [10, 22–24]. Irmak et al. proposed a thyristor controlled reactor (TCR) to acquire several parameters of a static VAR compensator in [10]. The remote monitoring software has been implemented by using an OLE for process control (OLC) server to provide current, voltage, power factor, and power measurements to graphical user interface (GUI) on the monitoring computer.

The sensor network and smart metering play a vital role in power monitoring of generation section. The measurement systems are improved from automated meter reading (AMR) to advanced metering infrastructure (AMI) systems with the integration of communication systems to power electronic devices. Wired and wireless communication methods are utilized to enhance monitoring and control features of SG applications. Kabalci et al. have proposed wireless monitoring and smart metering systems with wireless communication in [13, 24] and wired systems such as power line communication (PLC) [22, 23] and USB-based monitoring system in [12]. The USB-based monitoring system has been implemented for dual DC–DC buck-boost converter that is designed to interface PV plant. Each PV plant is controlled by a dedicated MPPT algorithm where the data acquisition process is also handled by dedicated microprocessors. The inherited data are sampled, measured, and converted to data packets for transmitting to PC over USB communication port as seen in Fig. 3.8. The communication system is optically isolated from power converter, and the acquired data are provided to USB port with UART communication protocol.

The monitoring systems inherit several data as the generated power rate, converter situation, energy consumption rates, real-time monitoring data, and control commands according to their design procedures. The monitoring infrastructure is comprised of GUI software that is coded with Visual C# as shown in Fig. 3.9 [12]. The GUI provides real-time measurement data on circular images and data graphics while the recent data can be recalled from database by defining any date from calendar application on GUI. The main organization is based on implementing measurement system with current and voltage sensors in the power circuit, transmitting the physical data to microprocessor for communication, modulating the data in microprocessor, and transmitting the modulated data to any receiver such as computer, mobile devices, or terminals. Once the measured and modulated data are acquired at receiving end device, it is stored in a database file and GUI inherits monitoring data from repository.

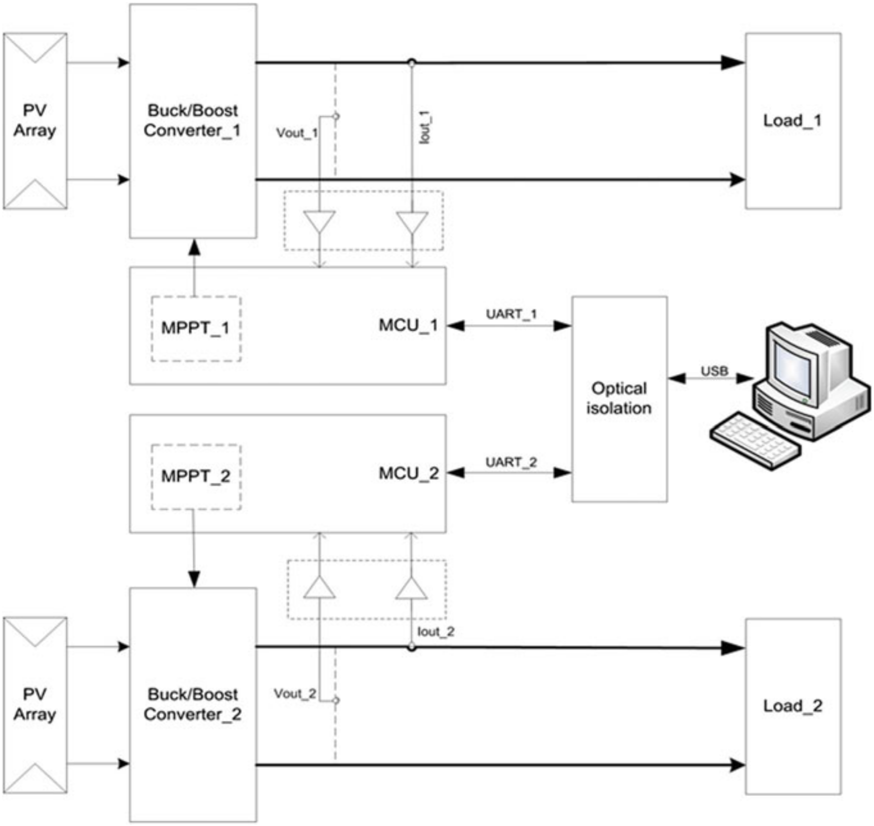

Fig. 3.8 Data acquisition and communication interface of DC converters

The wireless communication methods are widely used in rural areas and geographically spanned DERs since installation would require additional costs for wired communication.

Such a remote monitoring and remote control system have been proposed in [13] that complete block diagram is illustrated in Fig. 3.10. A data acquisition board is implemented to inherit all types of required data that act as a central monitoring device. The measurement device is equipped with several current and measurement sensors comprising the sensor network that detects power measurements from several nodes as shown in figure. The inherited data are modulated by a microprocessor and are transferred to server unit, which interacts with client and system administrator on a wireless communication infrastructure. It is also integrated with Internet cloud over 3G communication network that enables to reach monitoring and control system from anywhere. The remote control system includes an 8-channel relay-switching interface that is connected to several loads, and a cell phone connection is used to open and to close the loads.

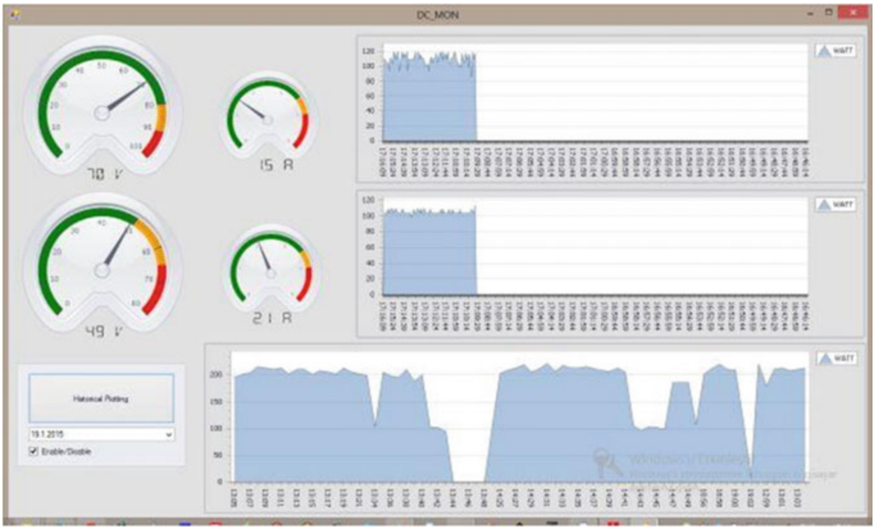

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Fig. 3.9 GUI software of DC–DC converters in a PV plant

The PLC is one of the most widely used methods among wired communication systems such as fiber optic, telephone lines, and so on. The digital subscriber line (DSL) provides data transmission rate up to 10 Gbps, while fiber optic provides 160 Gbps data rate at most. Although the data rate of PLC is relatively lower than both wired communication infrastructures, it provides reliability and insensitivity against interference causing mitigations in wireless communications. Two types of PLC technologies in narrowband and broadband have been improved to cope with interference and distributive effects of transmission channel. The bandwidth of narrowband PLC (NB-PLC) has been extended up to 500 kbps that increases coverage length of transmission up to 150 km in low-voltage or high-voltage lines. On the other hand, broadband PLC (BB-PLC) presents higher bandwidth up to 200 Mbps and higher-frequency operating at 250 MHz [5].

The PLC communication is based on shift keying digital modulation methods such as binary phase shift keying (BPSK), quadrature PSK (QPSK) or orthogonal frequency division multiple (OFDM) mainly. In addition to PSK, amplitude shift keying (ASK) and frequency shift keying (FSK) methods are rarely used in PLC communication since PSK is the most robust modulation method against inference among others. A PLC-based remote monitoring system has been designed to analyze as shown in Fig. 3.11 where communication system is implemented with QPSK modulator and demodulators as proposed in [22, 23].

The PV plants are located at geographically spanned areas and irradiation values are randomly changed to analyze DC bus voltage and operation of boost converters that are illustrated as DC–DC converters in orange boxes. The generated DC voltages are coupled on a unique DC bus at 640 V_{dc} that supplies three-level diode-clamped

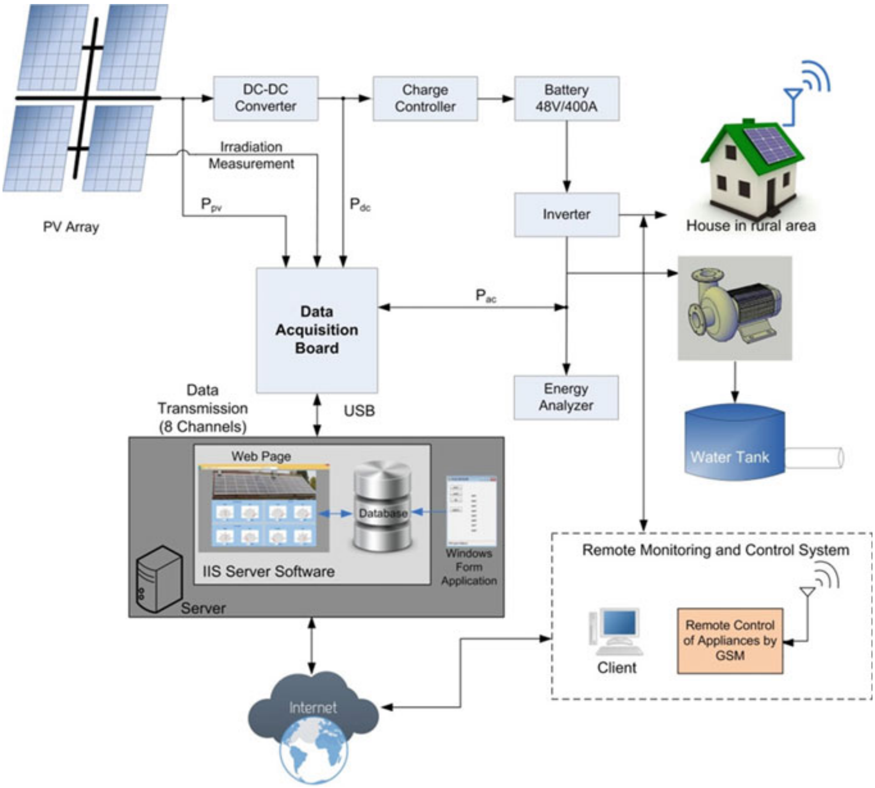

Fig. 3.10 A wireless monitoring and control system for a PV plant installed in rural area

multilevel inverter (MLI) . The irradiation values and generated DC output voltages of each PV plant are illustrated in Fig. 3.12a, while corresponding AC line voltages have been shown in Fig. 3.12b. The MPPT algorithms of each PV plant stabilize output voltages around 640 V_{dc} while maximizing harvested energy. The MLI output voltage is limited to 480 V 60 Hz that is generated at 15-level staircase output before electromagnetic inference (EMI) filter and the filtered output is obtained at the desired level as depicted with red lines in Fig. 3.12b.

The MLI system is implemented as a multi-string inverter that eliminates particular drawbacks of widely used central inverter or recent microinverters owing to its lower cost and optimal MPPT control features. On the other hand, the string diode losses that are met in central inverters and dedicated MPPT requirement of a micro-inverter is not involved in string inverter topology. The string input voltage is allowed to be high enough while the input power and number of string connections to DC–DC converter is limited. On the other hand, this limitation is coped with multi-string inverter topology that is improved considering the regular string inverters. Moreover, the multi-string inverters can efficiently interface various PV strings that

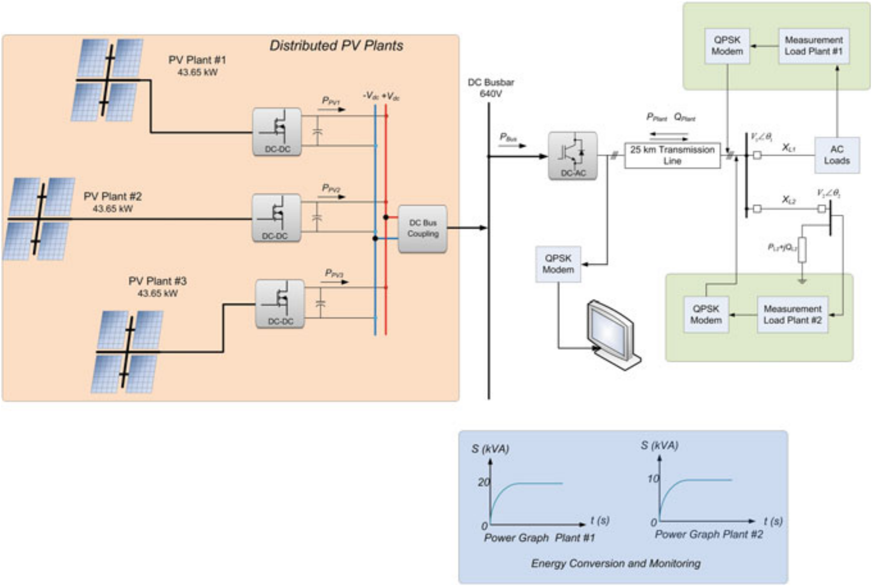

Fig. 3.11 Demand monitoring system for PV plants

are installed at various power levels due to its increased input voltage range. String and multi-string inverters are state of the art in RES and DER generation areas in terms of cost and power efficiency, and they allow to interconnection of several different types of sources together [25]. The control algorithm of MLI is improved regarding multicarrier sinusoidal pulse width modulation method (SPWM). The transmission line is modeled with real-time impedance values of conductors, and the length of line is set to 25 km, and the distribution systems are comprised of several load plants at the end of system [22, 23].

The load plants are designed with resistive and inductive loads to monitor power consumption rates over transmission line. The measured voltage, current, and phase angles are modulated by a QPSK modem that is designed according to given block diagrams in Fig. 3.13a, b for modulator and demodulator, respectively. The baseband signals to modulate are converted to parallel at the QPSK modulator input and then I and Q channels are generated regarding φ_n orthonormal basis functions where φ_1 and φ_2 stand for cosines and sine functions as depicted in Eqs. (3.1) and (3.2), respectively;

$$\varphi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t) \quad 0 \le t \le T \tag{3.1}$$

$$\varphi_2(t) = -\sqrt{\frac{2}{T}}\sin(2\pi f_c t) \quad 0 \le t \le T \tag{3.2}$$

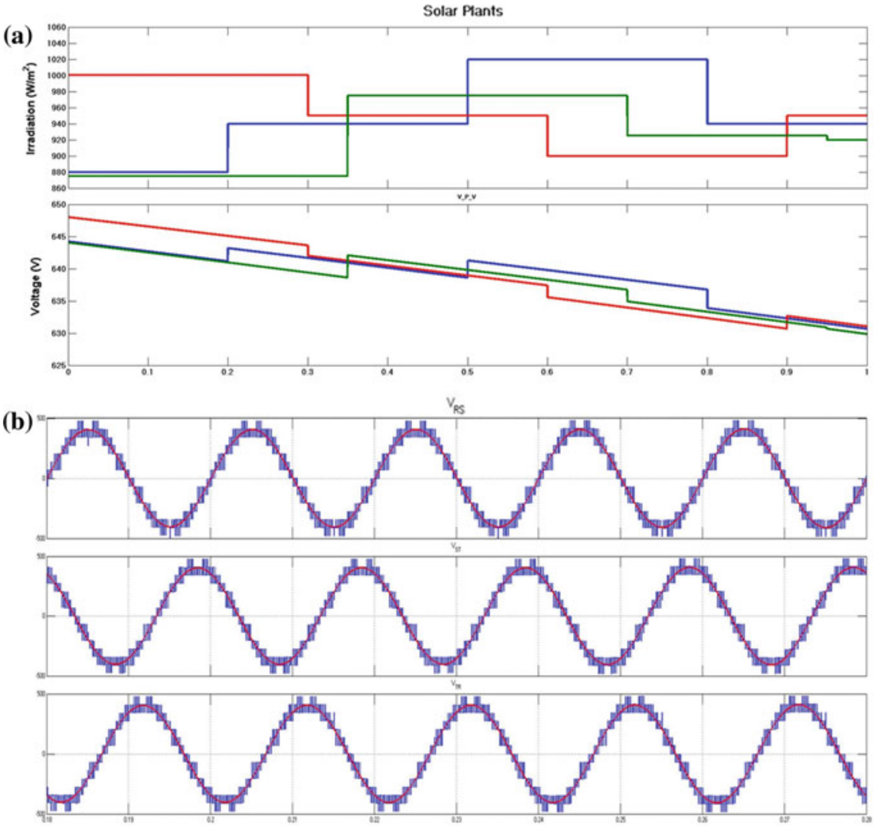

Fig. 3.12 Generation system analyses, **a** irradiation values and DC output voltages of each PV plant, **b** AC line voltages measured at the output of MLI inverter

where f_c is the carrier signal frequency and t is the period. The resultant QPSK signal is obtained with Eqs. (3.3) and (3.4) where A denotes the amplitude at each I and Q channel;

$$s_{\text{QPSK}}(t) = s_1(t) \cdot \varphi_1(t) + s_2(t) \cdot \varphi_2(t) \tag{3.3}$$

$$s_{\text{QPSK}}(t) = A \cdot I(t) \cdot \cos(2\pi f_c t) - A \cdot Q(t) \cdot \sin(2\pi f_c t) \quad -\infty < t < \infty \tag{3.4}$$

The odd and even signals are used to generate digitized data signal by $Q(t)$ and $I(t)$ signals [23]. The demodulator carries out three steps as signal detection, recovery and multiplication processes to inherit the data signal. After the carrier recovery step, the modulated signals are obtained at I channel and Q channel and are supplied to correlator and decision stages. The coherent multiplication process is applied to recover raw data, and synchronization signal is generated in the next cycle of demodulation process. The inference signals are eliminated at filtering stage where

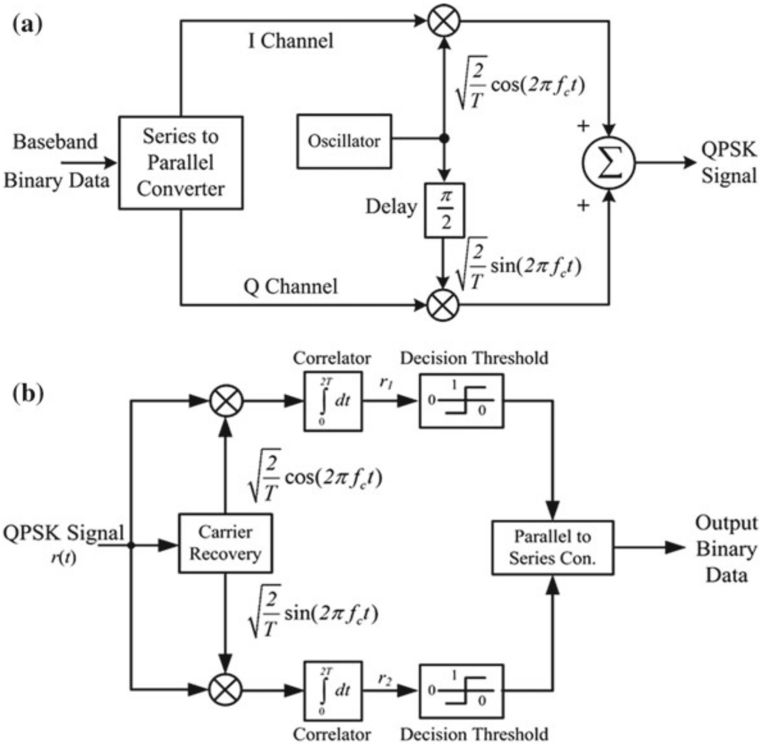

Fig. 3.13 Block diagrams of QPSK modem, **a** modulator, **b** demodulator

the received signal is inherited as logic "1" and "0" data. The BPSK modulator and demodulator that is simpler than QPSK is illustrated along transmission channel in Fig. 3.14

In BPSK modulation, different dual phases are generated at 180° phase difference or π radian in angular plane, and BPSK signals are analytically expressed as follows:

$$s_{\mathrm{BPSK}}(t) = \begin{cases} \gamma(t)\cdot(A\cdot\cos(2\pi f_{\mathrm{c}}t)\,, \text{ data} = 1 \\ -\gamma(t)\cdot(A\cdot\cos(2\pi f_{\mathrm{c}}t)\,, \text{ data} = 0 \end{cases} \tag{3.5}$$

A denotes the amplitude of carrier signal, $\gamma(t)$ denotes a random binary pulse with period of T_0., and f_{c} expresses carrier frequency. The level of $\gamma(t)$ varies between -1 and 1. The modulator and demodulator are integrated with transmission line by a coupling device comprised of R-L-C network on modem side and a series L-C filter on the transmission line side. These circuits are used to match impedance of both sides while magnetic coupling interfaces the low power digital signals.

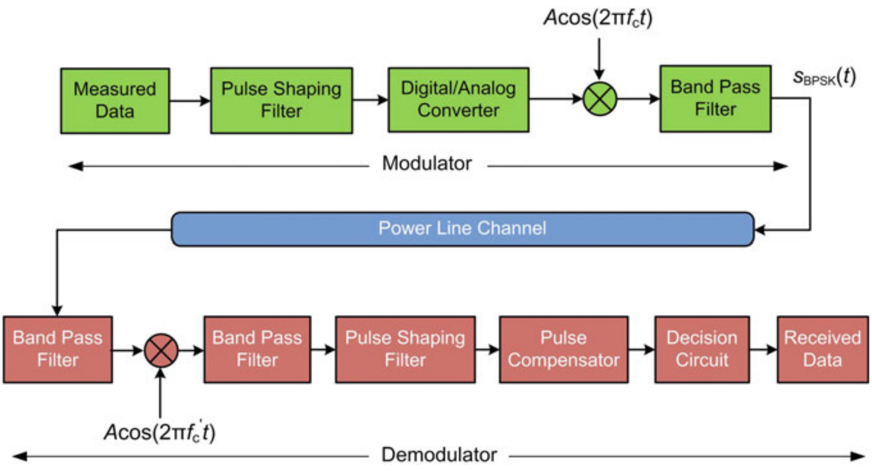

Fig. 3.14 Block diagrams of BPSK modem along transmission channel

The improvements in power electronics and integration of communication methods have enhanced SG applications in the context of remote monitoring, measurement, and control opportunities. The innovative SG studies are being implemented in terms of generation, storage, and modern applications including numerous electronics appliances that facilitate daily life at any aspect of usage.

3.3 Enhancements in Microgrid, Generation, and Transmission

An increasing attention has been focused on DG and DERs in last a few decades. It is accepted as an efficient solution against global warming and climate changes due to its various advantages such as high efficiency, reduction of carbon emission, minimizing transmission and distribution line losses, interaction with utility grid, and easily coupling structure for several different power sources. A DG plant mostly includes RESs as PV plants, wind energy sources, tidal and wave sources, biogas plants, ESSs and fuel cells as well as small and micro-hydro turbines as conventional sources. The local distribution systems based on DG plants are known as microgrids that are located at load plants or near to load locations. The microgrids are one of the most important technologies that contribute enhancement of DG systems. They can be operated in grid-tie or islanded modes according to power ranges in low voltage operation. Any grid-tie microgrid can also be converted to island mode operation during maintenance, faults, or disturbances. A microgrid copes with the intermittent structure of RESs such as PV or wind turbines with the support of additional sources that increase stability and resiliency [26, 27].

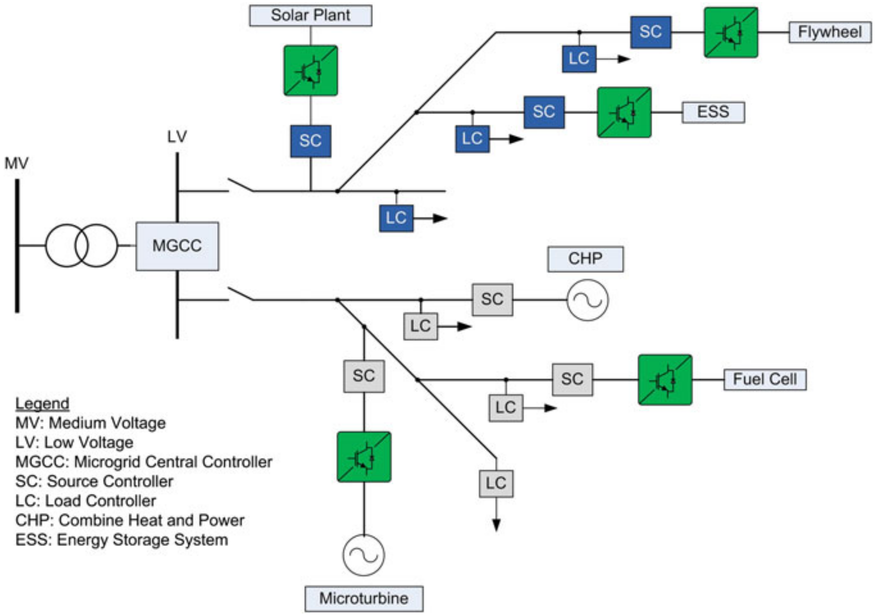

Fig. 3.15 Block diagrams of a microgrid scheme and MGCC

The high penetration of RES improves the capabilities of utility grid. However, the power quality and control operations should comply with several interconnection standards such as IEEE-P1547-2003, which presents a benchmark model for integration. The penetration of DERs to utility grid experiences several challenges in terms of technical, economical, and management aspects. Therefore, several control and management procedures have been implemented for microgrid and DG integration to utility grid. The technical challenges are handled in terms of power quality, efficiency, protection, voltage regulation, and stability. The microgrid central controllers (MGCC) that are improved for microgrid management are dedicated systems to accomplish DSM, DR control, and generation control duties. It regulates the voltage and frequency of the microgrid and sustains the system stability [4, 27]. The block diagram of a MGCC in the microgrid scenario is illustrated in Fig. 3.15 where LV section is controlled by MGCC, source controller (SC), and load controllers (LC). The MGCC compares load demand and generation level of microgrid and decides to increase the generation level or leaving some non-critical loads from microgrid to supply critical loads.

MGCC accomplishes this operation by controlling SC and LC subsystems in the microgrid. It is noted that MGCC can provide 21.56% of daily energy consumption by managing DR and generation control in [27]. Furthermore, MGCC can detect the instant power quality of microgrid at point of common coupling (PCC) and can improve power factor by connecting and disconnecting to the utility grid. The synchronization operation during reconnecting is also performed by MGCC.

Regardless of what controller type used among MGCC, micro-source, or decentralized controller, the microgrid controller improves resiliency and flexibility of power network to supply load without any curtailment or blackout. Besides, controllers decrease the operation costs, DER integration and usage rate, limits the carbon emission, and enhances reliability, sustainability, and security of sources. The microgrid controllers enable the power network to interface distributed management systems, DER aggregators, and distributed metering systems. The *Standard for the Specification of Microgrid Controllers* that is known as IEEE P2030.7 and *Standard for the Testing of Microgrid Controllers* (IEEE P2030.8) define several control requirements and performance measurements, respectively. The IEEE P2030.7 standard clearly describes core control functions in terms of transmission and dispatching. These core functions allow the microgrid to operate autonomously and manage its own functions to satisfy interconnection requirements.

The MGCC provides standardized and customable communication protocols in addition to its power management functions. It interfaces legacy SCADA systems with recent DER and demand management systems. Furthermore, it provides a scalable and reliable controller structure to users by facilitating integrating or removing any DER to microgrid [28]. In addition to MGCC, the supervisory control and energy management system (EMS) are required to control stability of microgrid. The microgrid management requires a comprehensive control infrastructure since power network is affected by technical and physical changes. An enhanced control and management system is comprised of standardized hierarchical control schemes that are known as primary, secondary, and tertiary control levels. The primary-level hierarchical control deals with control and regulation of local power generation, voltage, and current magnitudes. It provides stabilized outputs for predefined magnitudes by forcing micro-sources to track set values. The most widely used primary-level control method is droop control that is based on Q-V control or line impedance measurement. The secondary control is hierarchically located on primary level in order to manage power quality, voltage–frequency restoration, harmonic elimination and coping with unbalanced load situations. The secondary control is performed either centralized or decentralized structure. The centralized control is improved for small microgrids where the control principles are based on inner loop controls and mostly performed by manual methods. On the other hand, the decentralized control in secondary-level deals with voltage and frequency deviations of microgrid that are caused by load and generation-level variations. It is a more autonomous system compared to centralized secondary control since distribution network operator (DNO), MGCC, and LCs comprise the hierarchical structure. In addition to these, decentralized secondary control system can be managed by the aid of multi-agent systems (MASs).

The tertiary or third-level hierarchical control brings intelligence and communication capabilities to the microgrid. In this context, the information and communication technologies (ICT) that are used to transmit measured data and control commands are integrated in this control level. In addition to data acquisition; prediction and decision algorithms, microgrid observation, economic dispatch systems are improved and applied in tertiary control. The computational methods such as neural networks, genetic algorithms, particle swarm optimization (PSO) algorithms are used in this control level. The legacy control levels of secondary and tertiary control constitute microgrid supervisory control (MGSC) and EMS systems. The latency and bandwidths among hierarchical control levels are different from each other; i.e., the droop control in primary control has a response time around 100 ms while secondary-level control takes from 100 ms to 1 s and tertiary control can extend up to hours [29–31]. The hierarchical control schemes along a microgrid system are shown in Fig. 3.16.

The primary control provides voltage and frequency stability and facilitates penetration of new energy sources to microgrid. It also performs islanding detection to manage power flow through utility grid. The secondary control is responsible for compensating voltage and frequency deviations that are caused by primary level. In case of any deviation occurs after primary control, the secondary control regulates voltage and frequency values. The tertiary control is also responsible to MGSC and EMS operations with secondary control in addition to its power flow management and economic dispatch objectives [29–31].

Besides the hierarchical control methods, another important enhancement of DG and microgrid is virtual power plants (VPP) that improves SG applications in terms of communication and power networks. In fact, a VPP denotes an interface aggregating several DERS to comprise a single power plant. VPP enables numerous RES and DERs to operate in a dispatchable and efficient way owing to its energy storage and DR management capabilities. The utility grid controls the participation level of a VPP with market. Therefore, standardized communication infrastructures are required to improve efficiency, optimization, coordinated control with DERs and interoperability capabilities. The communication-enabled VPP systems provide numerous economic advantages such as scheduling of operation modes, DR control, data transmission, management, load prediction, and dispatch strategies to utility grid operators. Therefore, VPPs have become a certain component of smart grid infrastructures. The VPP structures are classified into two categories as technical VPP and commercial VPP that provides flexible and resilient capacity to electricity market for distribution service operators (DSO) [32, 33]. The ICT requirement of VPP is widely studied in the context of wired and wireless communication techniques. IEC 61850 and IEC 61968/61970 common information model (CIM) is the particular communication standards that are used to improve VPP services and information structures [32]. The reliable and efficient communication system plays a vital role in bidirectional data stream and power flow operation of VPP.

IEC 61850 standard has been based on several previous standards such as IEC 61400-25 that is improved for substation automation at transmission level, and IEC 61850-7 series that are prepared for substation and control center automation of hydropower plants and DER types in the scope of *TC 57 Power systems management and associated information exchange* study of IEC. The logic node structure and communication functionalities facilitated the enhancement of several equipment used for protection, management, monitoring, and communication aims that are lately named as intelligent electronic devices (IEDs). The IEDs are easily integrated with SCADA and EMS systems to perform automation objectives including control and communication. Another important fragment of VPP communication system is CIM based on IEC 61970 standard and used for interfacing EMS in transmission and

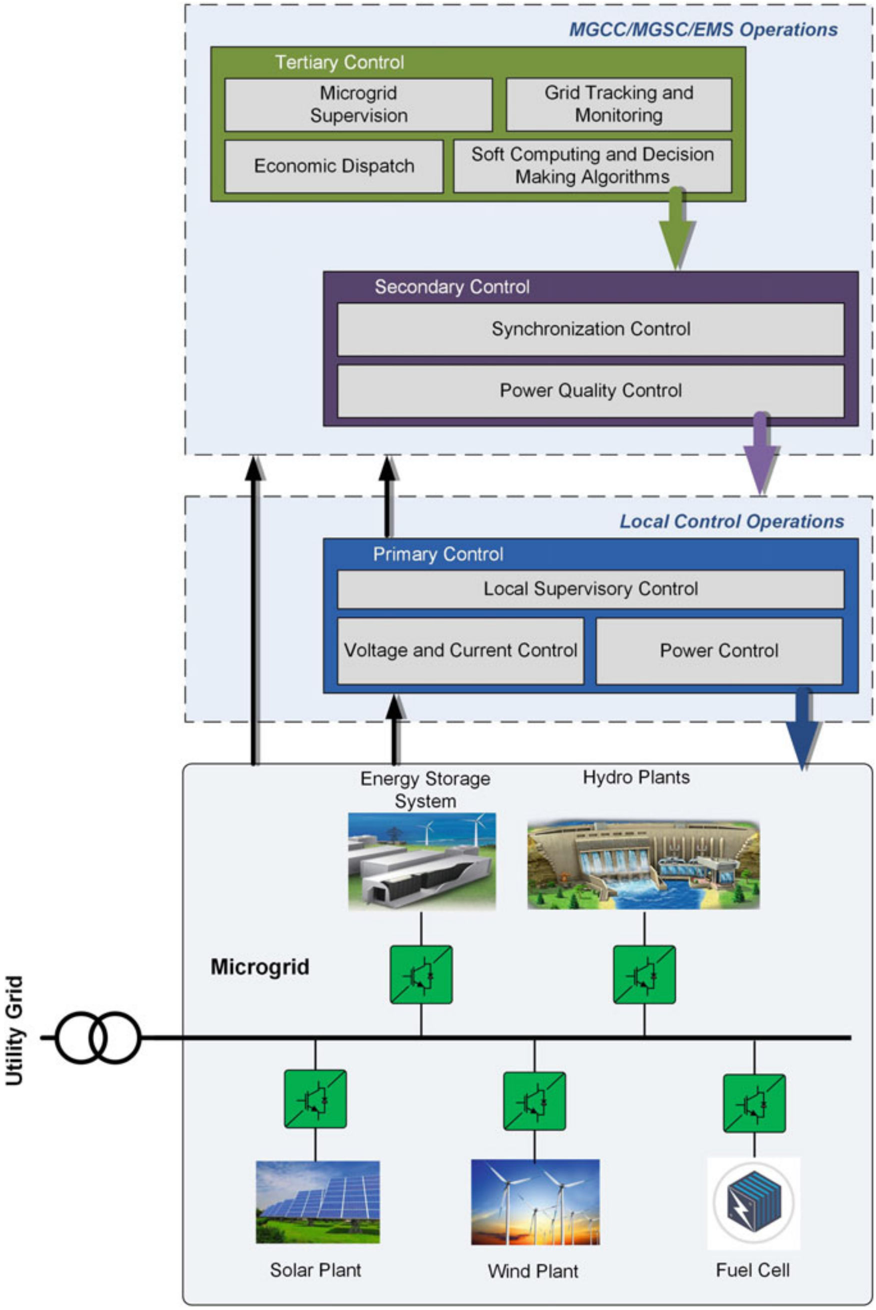

Fig. 3.16 Block diagrams of hierarchical control levels in a microgrid

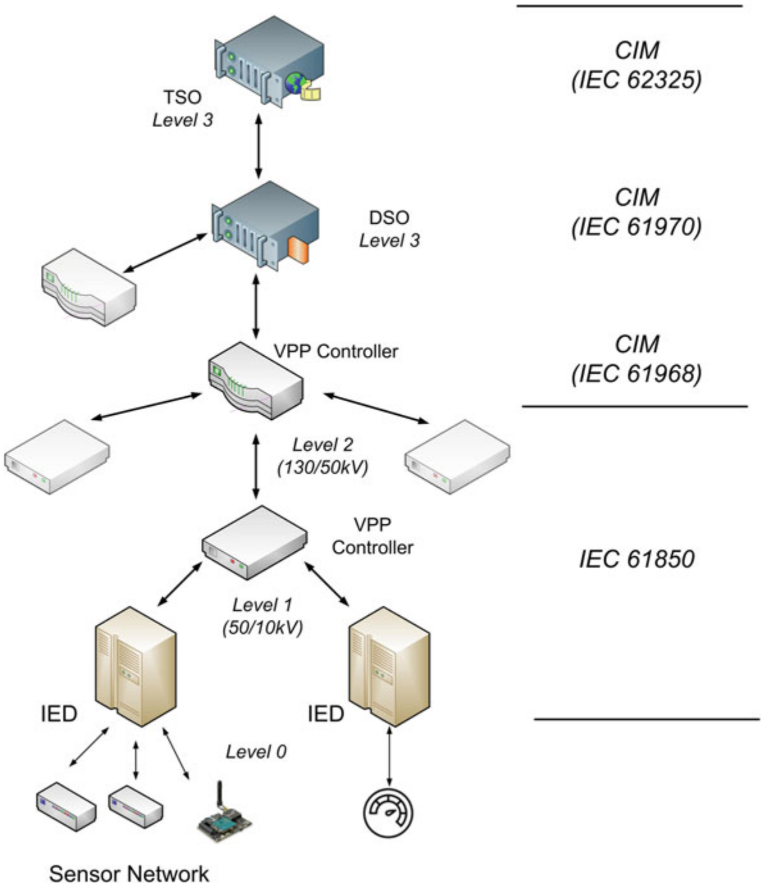

Fig. 3.17 Hierarchical architecture of a VPP system

distribution level as illustrated in the hierarchical architecture of VPP in Fig. 3.17. CIM has been enhanced for different purposes regarding two different standards; IEC 61968 for distribution level and IEC 62325 electricity market communication purposes [32].

The hierarchical model of a VPP system is used to provide data and information exchange between applications and EMS at distribution level. The model describes economical definitions such as management planning and billing. The transmission latency is taken into account in VSS management as well as in hierarchical control levels. The data acquisitions of grid magnitudes such as voltage, current, power, and DER generation levels are sufficiently performed in 1-min intervals. The day-ahead planning and forecast analyses require 15-min intervals to update for data acquisition. On the other hand, the critical measurements including power compensation, detection of voltage, and frequency deviation require fast response based on measurements less than 1 min. The illustrated hierarchical architecture can interact with any substation in the grid infrastructure over wide area network (WAN) at 100 Mbit/s bandwidth. The communication reliability is still a concern to obtain sensory data since inference affects wireless communication systems at substations. However, wireless local area network (LAN) is being practically used in distributed automation with IEC 61850 standard.

The number of measurement node and DERs in a VPP causes peaks in communication bandwidth. The solution to overlying problem is handled in IEC 61850-90-7 by randomizing response time in a defined time interval [32].

The substation automation system (SAS) is another component of microgrid structure along SG application, and it refers to an automation system utilizes acquired data from IEDs, control centers, and monitoring interfaces. SAS manages the substations considering the acquired data from field devices such IED, remote terminal units (RTUs), and PLC infrastructures, and thus executes SG requirements. The field devices are equipped with limited capabilities in terms of processors, memory, and license-free operating systems that they become vulnerable to external intrusions. The transmission and distribution substations require critical security precautions between MG control center and substations due to their locations.

The most certain security issues can be noted as integrity, authentication, authorization, availability, and non-repudiation in SCADA systems. Furthermore, widely known threats as modification, denial of service (DoS) attacks, man-in-the-middle (MiTM) attack, and interruption should be taken into account for security. The SAS is capable to be controlled remotely since the maintenance and management of a substation is required to be executed in a short while. Although the remote connection and control of a SAS provide flexibility in operation, it causes crucial intrusion attempts. The field devices are improved with several authentication features in the context of security where the policies are sustained in role-based access control (RBAC). The RBAC model can cause security deficiency when the password control cannot be achieved.

On the other hand, SCADA and SAS can become vulnerable to intrusions due to IEDs since they are not equipped with strong authentication and authorization capabilities. These critical situations are prevented by using active directory interfaces for security check systems in authentication stage. The SAS communication infrastructure must include at least one of the wired modems, wireless communication systems, and IP-based systems to connect field devices. A complete SAS architecture is illustrated in Fig. 3.18 with several communication infrastructures. The IEDs as filed devices in this scenario can be accessed local or remote connections according to maintenance, operation or control requirements. The WAN, IP-based networks, dial-up telecommunication network or cellular networks are used to connect substation controller (SSC). Therefore, authentication and authorization of users are critical for secure communication. The SSC manages substation-based authentication and access control of users owing to its access point and gateway structure. The certain certificate usage is a competent method in authentication of users since it can define users with several authorization rights. Attribute certificates and public-key cryptography certificates are used to designate user assignments [34].

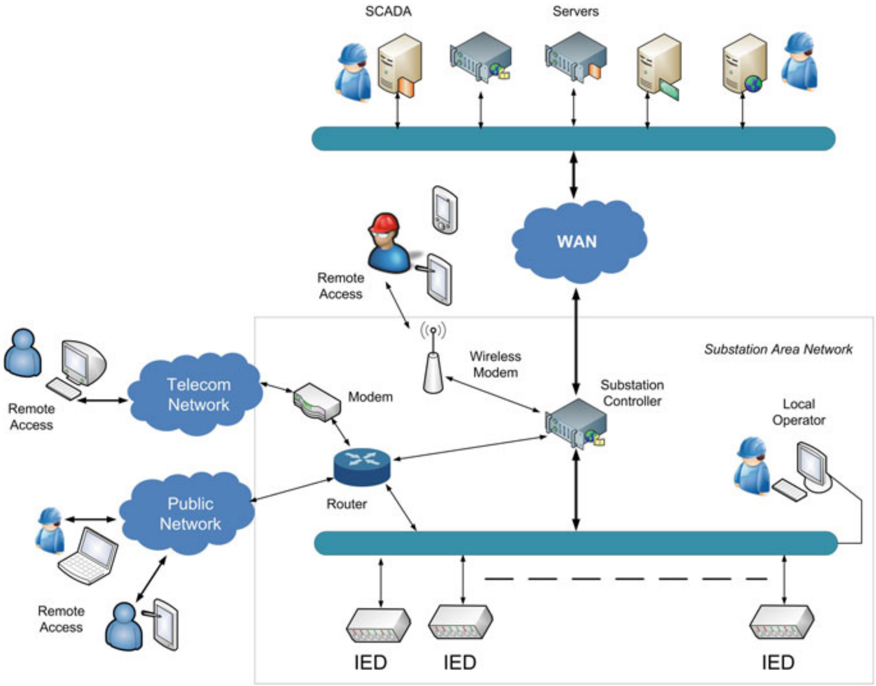

Fig. 3.18 Comprehensive substation automation architecture with various access configurations

3.4 Improvements on Demand Side Management and Smart Home Systems

The DERs have become essential component of a utility grid by the improvement and enhancement in SG control operations. However their intermittent structure, RES, and other sources are being widely integrated with conventional generation systems by successful applications. There are two main approaches lying behind this improvement that are generation backup systems, and DSM and DR control methods. The generation backup is achieved by integrating controllable conventional sources as hydro plants, CHPs, and natural gas plants to non-dispatchable wind and solar plants. In addition to the conventional sources, large storage systems that are introduced in the next section are also used to backup generation systems. The second method targets to improve and to manage market rule for controlling consumption behaviors and thus more flexible operation of conventional sources and RES integration is achieved. The DSM and DR schedules are improved for this purpose [35].

DSM programs provide a management environment for customer loads considering time and usage rates to diminish demand peak rates and thus redeliver power required by the loads. One of the most important contributions of this approach is to prevent gaps between peak demand and applicable energy at peak periods. Although

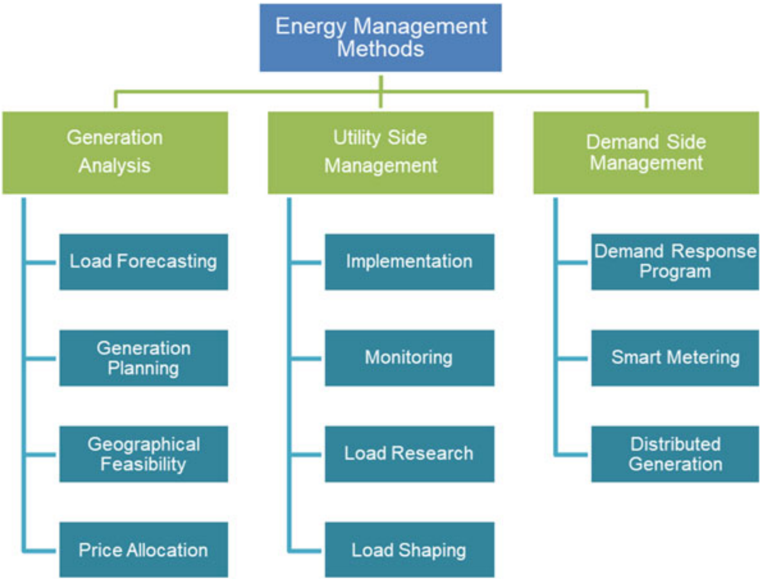

Fig. 3.19 Energy management methods at generation, utility, and demand side management

several management methods with several names of peak clipping, valley filling, load shifting, load shaping, and so on are applied on demand side, DSM is classified into two groups as direct load control (DLC) allowing operators to control partial share of customer loads directly and indirect load control (ILC) allowing customers to control power consumption by themselves. Regardless of control signal direction, DSM addresses to decrease peak demand of the system by shifting load density due to controllable loads and control operations [36, 37]. Energy management methods are classified into three categories as generation analysis, utility side management, and DSM as shown in Fig. 3.19. The DSM methods include DR program improvements, smart metering operations to detect load types and load management, and distribution generation management to improve energy efficiency. The load management program is performed to decrease the energy consumption and to shift the peak demand times to slighter times. The DLC can be seen as the easiest way to decrease energy consumption by controlling consumer loads, but it causes to privacy concern on demand side. This situation has been handled as a barrier on DSM in [37]. Indeed, it can be barrier to force consumers for changing their behaviors or stop the energy consumption, but providing several options and encouraging rewards that reduce electricity cost by managing their consumption shares in a day will be helpful for DSM.

Therefore, DSOs present various price strategies regarding varying demand time of a day. The SG applications enable bidirectional communication infrastructure that allows to have smart DSM by including computational methods such as artificial neural network (ANN), game theory, genetic algorithm (GA), mixed-integer nonlinear

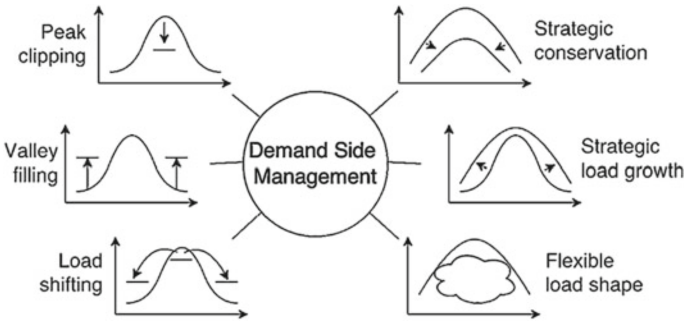

Fig. 3.20 Fundamental load control profiles [38]

programming (MINLP) and so on in residential and industrial peak demand control [36, 37].

A very generic graphic illustrating almost all aspects of DSM is presented in Fig. 3.20 that summarizes strategic conversion, strategic load growth, flexible load shape, load shifting, valley filling, and peak clipping operations at a glance.

The strategic conservation method decreases periodical energy consumption by increasing consumer efficiency and decreasing improper consumption. This approach is very extensive requiring incentives for novel challenges. The strategic load growth method aims to manage periodical energy consumption by using computational systems and requires more efficient equipment and sources to achieve the aims. Another significant method, flexible load shaping, brings a number of actions and planning strategies between critical loads and regular consumers. This method detects load types without removing security requirements. The load shifting approach defines scheduled work period for highest energy consuming loads. The valley filling method promotes energy consumption at off-peak durations. Thus, it becomes desirable to consume at these periods since the cost is lower and decrement on average price improves the efficiency of system. The discounts on cost encourage many users to change their behaviors. The peak clipping is based on removing loads and decreasing demand during highly loaded conditions. The peak time is decreased by DLC, consumer load shutdown or DG and thus peak demand is decreased [39].

The DSM is based on DR operation that defines consumers' energy consumption behaviors. It can be managed by aforementioned DSM methods and incentives on electricity price. Consumers are not aware of efficient energy consumption in conventional power system, and they are not supported by incentives. Therefore, DSOs can only control the generation sources in order to meet demand by source management. The current DSM environment enables DSOs to improve a number of DR programs for any type of consumers. It is noted that three types of consumers exist in the DSM context of SG [37]. According to this classification, the small number of consumers changes their usage behavior to peak load hours and do not change consumption rate for the rest hours. On the other hand, some consumers change their peak load to off-peak hours due to high price during peak load hours and tracks incentives. The left group disagrees to change their consumption behaviors during all hours. This consumer group sustains their energy consumption during high price peak load and peak load hours. There are several classifications are available for DR programs that are grouped as incentive-based and price-based programs [37] or DR programs with and without dispatch capability [40]. The incentive-based program (IBP) aims to change consumer behaviors by providing incentives as its name implies. The program allows consumers to control their own load individually. The methods used in IBP are DLC, interruptible load profile, demand bidding, and emergency demand reduction that are also known as DR methods with dispatch capability. On the other hand, DR methods without dispatch capability or price-based programs (PBP) include time of use, critical peak pricing, real-time pricing, and inclined block rate methods [37, 40].

The recent improvements in ICT enable consumers and residential users to manage their own consumption by using several remote monitoring and control infrastructures. These systems are widely defined as home automation system, (HAS), building automation system (BAS) or smart home management system (SHMS). Smart meters, communication infrastructure, router and gateways, sensors, and smart appliances comprise a smart residential environment. The metering and control data are managed by AMI infrastructure that controls information and communication data flow between consumer and central control system. The control environment that is illustrated in Fig. 3.21 can include control of video surveillance system, data cloud, lighting system, safety and security, home appliances, microgrid sources, and heating, ventilation and air conditioning system [41, 42].

An intelligent residential control system requires a number of smart devices, and infrastructures are also required. The aforementioned devices should be compatible with ICT interfaces and capable to perform desired control operations that are transmitted by management system. In addition to home appliances, the DG sources and their components such as inverters, converters, and control systems are required to provide IED features [42]. A general intelligent building concept that is widely mentioned in [42] is comprised of BAS, energy management, and grid interface system, and ICT interface of BAS system. The summarized three-layer structure is used to analyze any SHMS in such way. The BAS system that manages monitoring and control of entire system can be assumed as the core of SHMS. The energy management and grid interface systems is responsible for managing energy efficiency of entire system by controlling DG sources, ESS, smart metering systems, energy consuming appliances, and other residential utilities.

The third component of three-layer infrastructure is ICT interface that provides communication infrastructure to the previous systems. The ICT interface communicates with both BAS and energy management system. It enables users to operate entire system by using handheld devices, Web sites or similar authenticated-based software. SHMS and smart meter infrastructure are directly interacting systems with DR and DSM operations of DSOs. Therefore, such systems enable real-time pricing information and facilitate to run several DSM strategies that decrease the cost and help to improve particular management policies of utility companies and DSOs.

Fig. 3.21 Smart home management system infrastructure

Furthermore, it helps residential consumers to control their consumption rates and bills by selecting appropriate tariffs.

3.5 Improvements on Energy Storage Systems and Electric Vehicles

One of the most important contributions of SG is to merge the ICT technologies and utility grid. This improvement provides instant monitoring of power demand due to smart metering applications. The DSM and DR programs allow energy supplier to improve several interactive pricing policies in order to manage the power demand. The consumers can decide to connecting or disconnecting load at the certain time to benefit from DSM programs.

A particular approach to meet power demand by decreasing bulk power generation and reduce the effects of intermittent RES structure on utility network is to use energy storage devices that can be easily integrated into utility. The energy storage system (ESS) is assumed as a buffer that is located between utility grid and load side and the stored power can be transmitted to loads whenever it is required [43]. The ESSs can be in any form of chemical, electrochemical, electrical, mechanical, and thermal systems. The most widely used chemical ESSs are based on hydrogen, natural gas, biofuels, and liquefied petroleum gas (LPG) storage [44]. The chemically stored energy sources can be used to generate electricity depending to use of featured technologies.

Despite chemical sources, electrochemical energy sources are used to generate electricity without any converting system requirements. The most widely known electrochemical ESSs are batteries and fuel cells [44]. Both of these ESSs play innovative roles in energy storage applications in the recent SG integration. The fuel cells are widely used in DG sources as a storage system while the improvements in battery technology have fostered electric (EV) technology. The particular term used to define battery energy storage systems is BESS that is improved with EV technologies [45]. Another ESS profile is comprised of electrical ESSs where the capacitors and supercapacitors are being improved. Although a wide variety of ESSs has been improved, the fuel cells and battery systems for DGs and EVs applications are presented in this section due to their higher contribution to SG.

3.5.1 Fuel Cells and Power Conversion

The basic fuel cells were discovered in early 1800s by reversing the electrolysis process. Fuel cells are static energy conversion devices due to their chemical reaction that generates electricity and exhausts water. The conventional diesel generators and similar engines generate electricity by chemical processes with lower energy, while fuel cell provides higher efficiency comparing others. Due to chemical and electrical structure, fuel cells have been assumed as a combination of advantageous features of engines and batteries. Fuel cell has been widely researched and experienced starting since mid-1900s [46].

The block diagram of a fuel cell that is essential to explain operating principle is illustrated in Fig. 3.22. The fundamental structure is comprised of two electrodes as anode and cathode to construct output terminals at both sides of fuel cell. The medium section between anode and cathode constructs the electrolyte membrane permitting the flow of positive ions to pass from anode to cathode and prevents negative ions to pass. The recombination of positive and negative ions with oxidant is occurred at cathode.

The electricity is generated by electrochemical reaction that occurs between hydrogen and oxygen in the water, which is reverse electrolysis process. The reaction of anode, cathode, and total electrical energy generated by a cell are calculated as shown in followings, respectively [47–49];

$$\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{H_2O} \tag{3.6}$$

$$\mathrm{H_2} \rightarrow 2\mathrm{H^+} + 2\mathrm{e^-} \therefore \mathrm{E^0} = 0\mathrm{V} \tag{3.7}$$

$$2\mathrm{H^+} + 2\mathrm{e^-} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{H_2O} \tag{3.8}$$

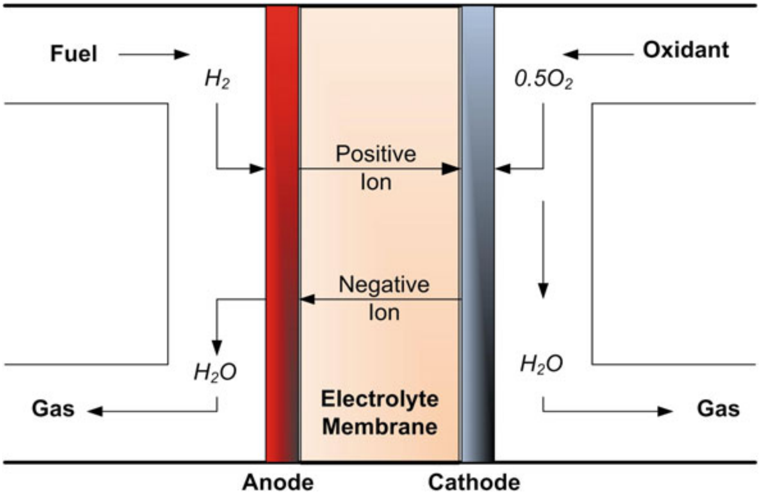

Fig. 3.22 Block diagram of a fuel cell

$$H_2 + \frac{O_2}{2} \rightarrow H_2O \therefore E^0 = 1.229V \tag{3.9}$$

The fuel cells are produced by using various electrolyte and fuel type where six major groups are known as alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell (DMFC). AFC was the very early fuel cell technology, and it was based on potassium hydroxide in water and alkaline electrolyte to generate electricity. The PAFC uses liquid phosphoric acid to generate electricity as its name implies. It has been improved during 1970s and has been widely accepted due to its stability and performance features.

Then, SOFC has been implemented with solid oxide electrolyte that increases the stability, efficiency, and fuel flexibility of previous fuel cells. MCFC was the first one operating at high temperatures over 650 °C comparing the aforementioned fuel cell technologies. Platinum electrodes and water-based acidic polymer membrane electrolyte comprise PEMFC. Its operating temperature is commonly lower than 100 °C. Its most important feature is higher power density comparing other fuel cell types that allows to be used in electric vehicle (EV) applications while the lower operating temperature makes it appropriate for transportation and commercial applications. However, the efficiency of PEMFC is not higher than 50% which is a significant drawback [46–48].

Another important application area of fuel cells is related to microgrid systems along smart grid infrastructures. A microgrid architectural design is illustrated in Fig. 3.23 where wind plants, solar plant, and fuel cell stack are coupled on a DC busbar [49]. The fuel cells are used as a backup source in such applications to cope with intermittent structure of wind and solar energy sources. The modeled and

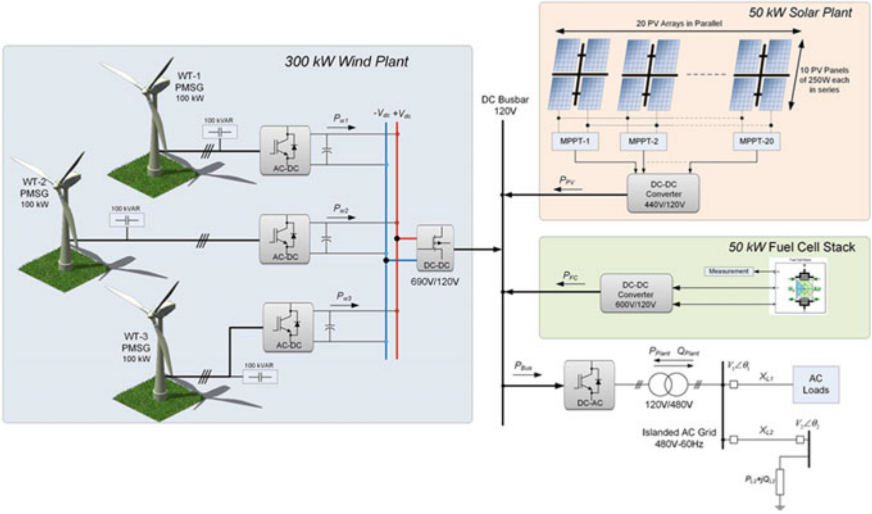

Fig. 3.23 A microgrid system including fuel cell stack

analyzed fuel cell model has been designed in PEMFC structure that is comprised of hydrogen and nitrogen blend fuel composition. The rated power has been set to 50 kW where the DC voltage at 80A is 625 V with 85% efficiency [49]. The output voltage of fuel cell stack is converted to the appropriate voltage level in order to be connected to DC bus. In case of any intermittence or curtailment occurred in solar and wind, the power is recovered by fuel cell in this way.

The fuel cell-powered systems can be integrated with battery banks to improve recovery capacity and resiliency of the system. The block diagram of a power conversion system that is mainly supplied by a fuel cell is illustrated in Fig. 3.24. A capacitor bank regulates the DC bus while battery bank supports this power conversion infrastructure to improve the resiliency of entire system.

It is a hybrid DC system where the generated voltage is regulated at first DC–DC converter and then increased in the second DC–DC converter that acts as a voltage doubler. Both converters are isolated over a high-frequency transformer. There are a wide variety of controllers used in this configuration. An algorithm that operates as an MPPT algorithm calculates the input power of system, but it also tracks the state of health (SoH) of battery and compares state of charge (SoC) magnitude with fuel cell. The net power calculated by this algorithm is used to generate switching angles at phase-locked loop and PWM generator blocks. Thus, the DC–DC conversion rates are determined and DC bus is supplied by battery bank and fuel cell. The AC line voltage generation is performed at inverter section that is controlled by a hysteresis controller. The input data of controller are provided by the PLL and phase conversion blocks. The dynamical power demand of loads is calculated at a power calculation algorithm regarding output voltage and current of inverter. Therefore, the input power

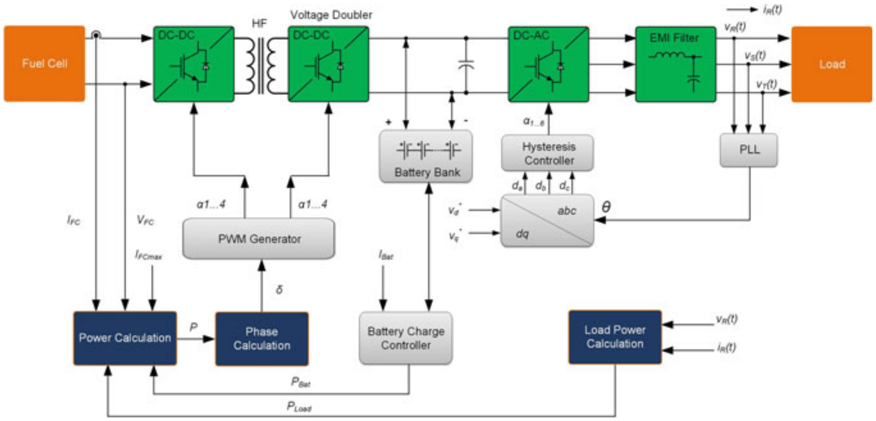

Fig. 3.24 A hybrid energy conversion system with fuel cell and battery bank

is controlled to manage DR and batteries are included to generating source to meet the demand if the power of fuel cell is not adequate.

3.5.2 Electric Vehicles and Smart Grid

EVs are experiencing extensive and rapid enhancements since a few decades due to their several usage advantages in terms of cost and operation comparing to internal combustion engine (ICE) vehicles. EVs are categorized into three basic types as hybrid EVs (HEVs), battery EVs (BEVs), and plug-in HEVs (PHEVs). The HEVs are operated by using both engine types as ICE and electrical motor that is not possible to charge externally. On the other hand, the BEVs that are based on pure battery-powered electric motor and PHEVs can be externally charged by plugging to any charge station. The charger of PHEV and BEV is directly connected to distribution network, and it charges batteries by using its AC–DC converter. Although the regular charge takes long time to fully charge the batteries, fast charge can be achieved by using particular and high-efficiency DC–DC converters [50]. The EV operating modes are noted as charge-depleting (CD) mode that refers to supply motor from batteries at startup. BEVs are capable to operate just in this mode. On the other hand, charge-sustaining (CS) mode that is available in HEVs and PHEVs provides to sustain EV to operate during low SoC of batteries. The CS mode allows to operate EVs in all-electric range (AER) operation that improves fuel economy of PHEVs [51].

The integration of many EVs to utility grid is a significant challenge for DR and smart grid issues. The charge and discharge cycles of EVs require well-planned operations and management in order to cope with high demand potential. The charging processes are listed as slow charging that takes up to 20 h for BEVs and fast charge that is completed almost in 15 or 20 min. A robust energy management system (EMS) is involved to manage charging operations along smart grid where metering, analyzing, and operating processes are realized [52]

The discharge of EVs that is defined with V2G terms is another important aspect of EVs in the context of smart grid applications. A general V2G, vehicle-to-home (V2H), and vehicle-to-vehicle (V2V) interaction is illustrated in Fig. 3.25 [53]. The V2G operations can be performed in either unidirectional mode or bidirectional mode regarding power flow capability. In unidirectional mode, the interaction is just based on charging the battery where the power flow is from grid to batteries of EV.

It is mostly preferred due to cost issues since the basic converters and controllers are adequate to realize this operation mode. However, this operation mode forces utility grid and can cause overestimated load during peak hours. The bidirectional V2G provides two-way power flow as its name implies. The power converters used in this mode are AC–DC converters to rectify grid voltage and DC–DC converter to regulate charging voltage of batteries. The DC–DC converter is also operated in bidirectional mode due to improved current control methods, and it is operated at step down mode during charge and step-up mode during discharge cycles. On the other hand, the AC–DC converter can act as a rectifier at charge cycle and as an inverter during discharge cycles. Thus, bidirectional operation is achieved. These operations provide active and reactive power control, power factor correction, and power regulation flexibility to DSOs. Furthermore, the RES integration to this infrastructure can be easily done in order to increase the reliability and flexibility of the utility grid. The DG sources and microgrids can be penetrated at MV and LV levels [53].

The active power control provides peak shaving and load management opportunities. The charge periods are shifted to out of peak hours, and discharge is encouraged on peak hours by the DSM programs of DSOs [53]. Therefore, EVs can be charged mostly at night. The widely used charging profiles are based on AC Level 1 at 110–120 V or AC Level 2 at 220–240 V charging tools. It is noted that AC Level 1 charging profile can add up to 5 miles range extension, while AC Level 2 adds up to 20 miles extended range per hour of charge. The EV charge schedule should be coordinated with smart home appliances by using home area network due to smart grid system. One of the most recent charging technologies is provided by wireless power transfer technique in addition to AC Level 2 or fast charge systems at public charge stations [54].

The charge control can be managed by using centralized or decentralized coordination methods. The centralized charge control optimizes the charge duration and scheduling after inheriting several data on required power rate of EVs. The collected data include the SoC, SoH, maximum battery capacity, and charge features of batteries. The optimization algorithm is run regarding inherited data, and the scheduled charging is get started by the station. On the other hand, decentralized charge control is operated by the data aggregation that is performed by the EV, and it coordinates with charge station to determine its own charging schedule [54].

The AC Level 3 is a new charge system that supplies 130 kW for rapid restoration of battery SoC by its three-phase 480 V power supply. The charge control of any PHEVs should be optimized and scheduled by using intelligent algorithms to pre-

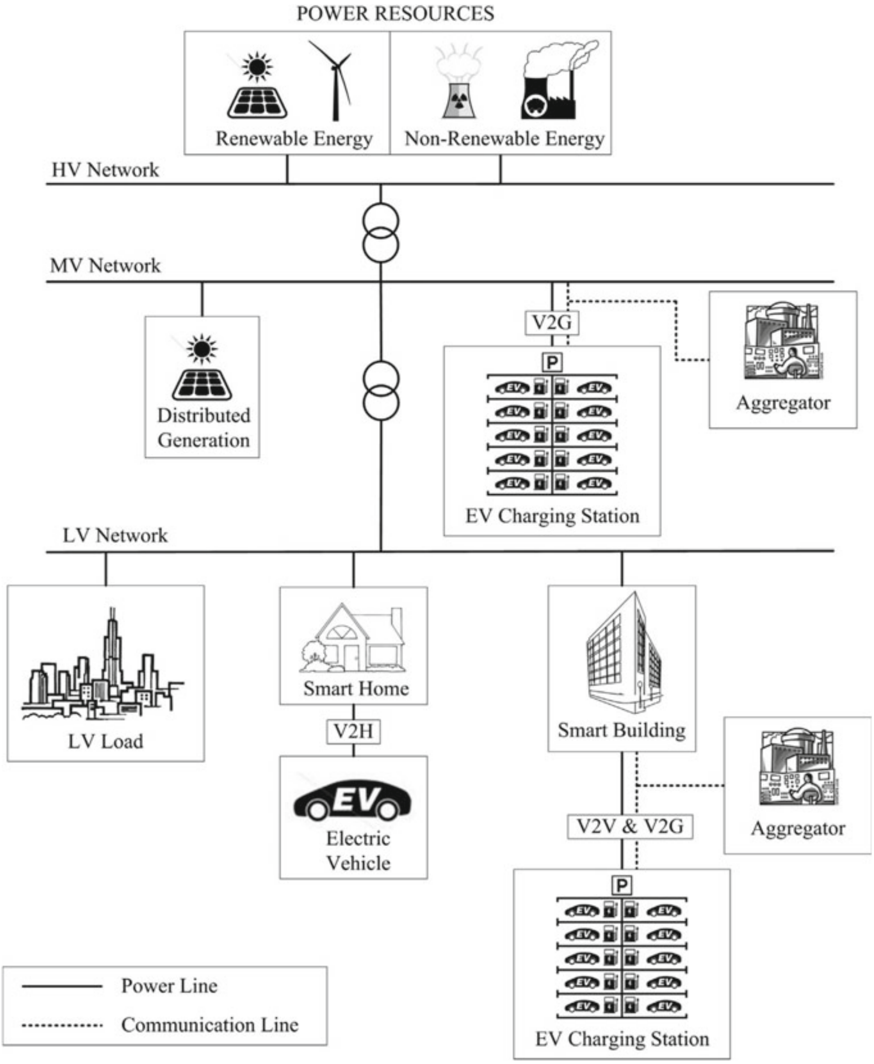

Fig. 3.25 V2G and G2V interaction along smart grid [53]

vent random demand since it causes unexpected deterioration in power quality and grid capacity. A common charge infrastructure is shown in Fig. 3.26 where the communication and sensor networks are particularly expressed. The intelligent charging system involves communication systems to provide instant and continuous monitoring of utility grid and data acquisition interfaces to obtain several data from sensor networks [55].

The acquired data are processed and analyzed in order to detect the required power rate, active and reactive power values, and power quality. The improvement

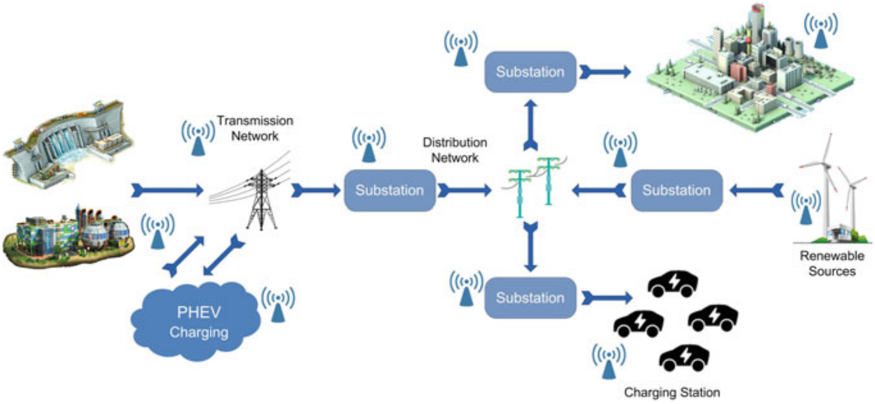

Fig. 3.26 PHEV charging system in smart grid with communication and sensors

of smart grid and communication systems has leveraged EV charging optimization and scheduling processes [55]. In contrast to its enhanced structure, the smart grid and V2G system integration are ever vulnerable to cyber-attacks that can be caused by authenticity-, availability-, confidentiality-, and integrity-related issues. There are major researches which have been proposed to mitigate the cyber-attack risks on EV charge systems as well as other smart grid applications [56].

3.6 Conclusion

The recent SG applications have drawn much more featured profiles comparing to previous phases. At the beginning, the SG has been improved by integrating ICT technologies to existing conventional grid. The bidirectional or two-way data and energy flow capability have been brought to smart grid infrastructure due to emerging communication methods, network structures, and developed power electronics. On the other hand, there several power sources and energy generation structures have been improved and integrated with existing utility grid. The microgrid was one of the most recent power infrastructures that enable DSOs to integrate various DERs to integrate their conventional generation sources. The microgrids have also been used by consumers where they participate to generation and can be shifted to prosumers.

The emerging technologies have been presented regarding power electronics, communication systems, microgrid generation systems, ESSs, and EVs that are most recent and innovative technologies promoting the improvement of SG infrastructure. The solid-state transformer and communication-enabled power converters have been analyzed in detail. The ICT-enable power converters have provided a novel research area to smart grid technology by facilitating remote monitoring and remote control. The smart meters, remote control system, and wide area networks integrated with sensor nodes are applied in generation, transmission, and distribution networks as well. The DSM and smart home management systems are another improvement brought by smart grid applications, and also, they have improved the smart grid environment for DSOs and consumers.

The energy storage technologies are seen as particular contributor on smart grid improvement. The chemical, electrical, and electrochemical storage systems have been interfaced at any layer of generation or distribution. The microgrid systems equipped with batteries and fuel cells have been realized to overcome intermittency and curtailment in microgrid structure. On the other hand, the widespread use of EVs has brought a novel vision to smart grid studies where EVs can react as ESSs during their discharge cycles. The surveyed and presented technologies have improved capabilities of smart grid infrastructure while they provide robust solutions to the challenges.

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