Chapter 2
Applications and Requirements of Smart Grid

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Abstract The electricity delivery infrastructure—consisting of power plants, transmission lines, and distribution systems—is known as the power grid. The power grid in its present form is one of the most remarkable engineering developments. The grid infrastructure has played a critical role in making electric power reach the common people in a reliable and economic way. The National Academy of Science, USA, has ranked the power grid as the most beneficial engineering innovation of the twentieth century. Power grid is a complicated and highly meshed network. The complexity of the grid has been ever increasing with the increase in electricity demand. The high reliability and power quality requirement for the digital society are challenging. The smart grid is a power grid that uses real-time measurements, two-way communication, and computational intelligence. The smart grid is expected to be safe, secure, reliable, resilient, efficient, and sustainable. Measuring devices like phasor measurement units (PMUs) can radically change the monitoring way of the grids. However, there are several challenges like deployment of sufficient number of PMUs and managing the huge amount of data. Two-way communication is an essential requirement of the smart grid. A communication system that is secure, dedicated, and capable of handling the data traffic is required. The integration of renewable sources will alter the dynamics of the grid. This situation calls for better monitoring and control at the distribution level.

Keywords Smart grid · Power grid · Self-healing grid · PMUs

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2.1 Introduction

The electric power grid may be defined as the network of power lines, transformers, and other associated equipment employed to carry electric energy from the power plants to the consumers distributed throughout a region.

The region may be a small locality, it may be a particular region in a country, or it may also refer to an entire continent's electrical network. In fact, the electric power grid is one of the most complex man-made systems. In the USA alone, the electric network includes about 15,000 generators which send power through 339,000 km of high voltage transmission lines. The network has about 5600 distribution facilities [1].

Figure 2.1 shows the conceptual structure of the electric power system. It can be seen that there are three main sections of the network: generation, transmission, and distribution.

The primary objective behind implementing a system of such daunting complexity is to ensure very high reliability of supply, which is not possible with a small number of generators. The main benefits of an interconnected power system are:

1. Mutual assistance during emergencies, when the spinning reserve of one system may be made available to others. If each system operated independently, it would be necessary to install and operate additional generating capacity.

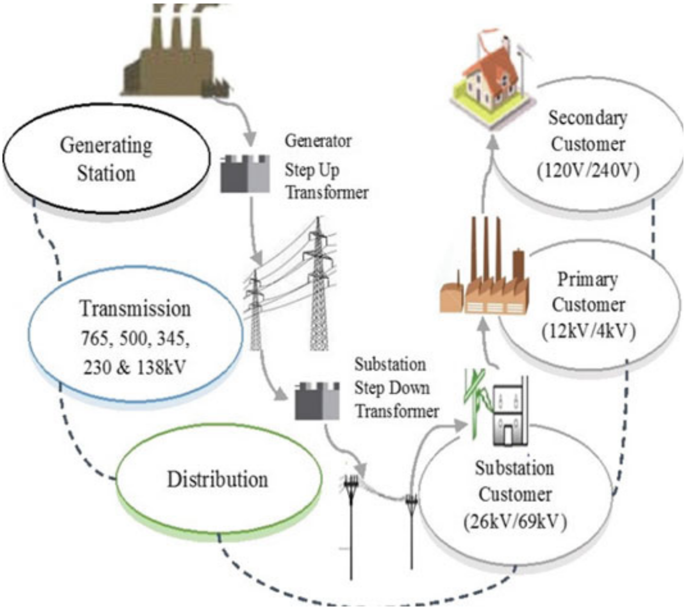

Fig. 2.1 Components of an electrical power grid [2]

2. Availability of thermal backup for hydro particularly during periods of low stream.
3. The peak demand on each individual system may occur at different times, this diversity resulting in a reduction in the overall system demand on the interconnected pool.
4. Availability of alternate source of supply during periods of forced outages or planned outages for maintenance purpose.

The power grid is a complicated and highly meshed network. The complexity of the grid has been ever increasing with the increase in load. The transition of the whole society toward digital systems has put strenuous requirements on the grid to maintain highly reliable and quality power. In order to better maintain the grid recent developments in sensing, computation, communication, and control have to be utilized.

The operation of a traditional grid is constrained due to the fact that electricity cannot be stored at a large scale and the grid operators have no control over the consumer's demand. Therefore, the grid equilibrium can only be established by continuously balancing the output of the central power plants in order to maintain a balanced condition. Most of the components in the traditional grid do not contain any intelligence or decision-making capability.

The smart grid can be regarded as a power grid that uses real-time measurements, two-way communication, and computational intelligence in an integrated fashion. The objective is to develop a system that is safe, secure, reliable, resilient, efficient, and sustainable. The smart grid is expected to be more resilient and self-healing in case of a disturbance. Integration of environment-friendly renewable energy sources is an integral part of the smart grid. The load curve is expected to be flattened by initiatives like demand response. This will eliminate the requirement of costly infrastructure required for peak demand. Consumers will actively participate in the smart grid through appliances like smart meters.

The implementation of smart grid requires better monitoring, communication, and control. Measuring devices like phasor measurement units can radically change the way grid is monitored. However, there are challenges like deployment of sufficient number of PMUs and managing the huge amount of data generated. Two-way communication is an essential requirement of the smart grid. A communication system which is secure, dedicated, and capable of handling the data traffic is another area of work. The integration of renewable sources—mainly at the distribution side—will alter the dynamics of the grid. This situation calls for better monitoring and control at the distribution level.

In the following sections of the chapter, the problems associated with the conventional grid are examined. The basic concepts, features, and technologies involved in the development of a smart grid are described. The key technologies required for implementing a smart grid are discussed. The important requirements on these technologies and the challenges to be addressed are also identified. Some of the important developments worldwide in the area have also been covered.

2.2 Evolution of Power Grid

The period from 1880 to 1930 constituted the formative years of the electric power system. Pearl Street Station in the New York City became the first central electricity generating station. It consisted of a bank of steam generators using a 100 V direct current generation and distribution system used primarily for illumination [3]. Since the low voltage involved restricted the distance of power transmission, most of the early power systems operated in isolation serving a small area only. In the Chicago city itself, 45 different utilities were serving electricity to the consumers. Geographically dispersed electric power companies in the USA started consolidating their operations from 1910, recognizing the economy involved by building large power plants and transmitting the resulting electricity over increasingly longer distances. Soon small areas were linked into single systems, followed by the interconnection of regions and states. These initiatives laid the foundation of technological idea of great importance—a single, unified power system covering a huge region, an entire nation, or perhaps someday a whole continent.

For more than half a century, large interconnected power systems saw an exponential rise throughout the world. The first serious blow to the concept came from the 1965 blackout of America which brought out the power engineers from their comfort zone of “golden age” [4]. The blackout raised serious questions about the reliability of large interconnected power systems because apparently it was this interconnected nature of the system which led to a complete failure of power supply to large metropolitan communities within just 12 min of failure of a small relay hundreds of miles apart. Such type of cascading failures originating from a trivial event is due to the interconnected nature of the grid.

The electric power system consists of a large number of interconnected elements forming a geographically huge and complex dynamic system generating, transmitting, and distributing electric energy to a large area. Because of its nature, a number of dynamic interactions are always present in the power system. These interactions may generate disturbances of a wide variety as the operating conditions change. In terms of power grid, a disturbance is defined as any unplanned event—including an outage—that produces an abnormal operating condition. Important thing about the power grid dynamics is the variation involved because of the interconnection of different nature components. There are wave, electromagnetic, electromechanical, and thermodynamic phenomena occurring continuously in the grid. Physical nature and laws governing these phenomena are entirely different. Moreover, these phenomena occur within different time frames. There are phenomena like wave effect and switching over voltages occurring in milliseconds. Actions like state estimation involve time frame of seconds, while load forecasting is done for a few days to few months. A detailed description of the variation in time frame in the grid phenomena is presented in [5].

The effect of some of these dynamics is local in nature affecting only individual elements of the system, while some of these dynamics can affect the entire system. The most important concern for grid operators is that how the grid will react to this wide range of dynamics with a change in power demand and to various types of disturbances in the system.

2.3 Problems with the Conventional Grid

The power grid is a highly meshed complicated network. The grid has evolved in this form because of the resulting increased reliability in an economic way. Different parts of the system have multiple generation and transmission alternatives as backup in case of a disturbance. The meshed network structure of the grid, however, makes it prone to cascading failure—called blackout—originating from a minor problem in a small section of the grid [6]. In a highly meshed network like power grid, the basic reason behind a blackout is the loading limit of the lines. If any line in the network is overloaded and more power is forced through, it may trip the line. Sometimes, this leads to a chain of cascading low probability events leading to blackout.

There are studies reported in the literature showing a direct relationship between the number of blackouts in the power grid and increase in interconnectedness of its components. The North American Power Network believed to be one of the robust grids in the world has seen a steady increase in the number of blackouts in recent years. The number of such blackouts in the North American grid has increased 124% from the duration 1991 and 1995 to the period between 2001 and 2005 [7]. Similarly in the Indian grid also, blackouts have increased as the utility has increased the interconnections between regional grids [8].

Deregulation of the power market has also caused a significant increase in the probability of cascading failures in the grid. For example, the Italian blackout of 2003 originated from a seemingly routine event of a tree falling on a line somewhere in the network. One of the main reasons of this event leading to a catastrophic blackout was at the time of fault the grid was importing 6000 MW low-cost power from neighbors. This blackout is considered one of the worst blackouts in Europe ever affecting 57 million people [9]. A summary of major blackouts in the world and their impact is given in Table 2.1 [9].

Complete prevention of large-scale blackouts in the power grid cannot be ensured. These blackouts are the result of extremely low probability events of beyond $(N - 2)$ contingency. The conventional arrangement in the power network is to take care of the $(N - 1)$ contingency events. Designing a power grid considering all such low probability events is not feasible because of the economics involved with the present arrangement. Different modeling and simulation studies reported have shown that blackouts will continue to occur [10–13]. The way forward is to make provisions for early detection of faults in the grid. Even if a fault occurs, the faulty part should be quickly disconnected so as to prevent the fault from propagating to other healthy parts of the system. Developments like deregulation of the power market have made it more important to improve the monitoring and control in the power grid. The studies reported have also demonstrated a 325% increase in the probability of a blackout in the deregulated power market compared to the conventional.

Table 2.1 Summary of cascading outages around the world

Location	Date	MW lost	Affected people	Collapse time	Restoration time
US Northeastern	Nov 9, 1965	20,000	30 million	13 min	13 h
New York	July 13, 1977	6000	9 million	1 h	26 h
France	Dec 19, 1978	29,000		26 min	5 h
US Western	Dec 22, 1982	12,350	5 million	NA	NA
Sweden	Dec 27, 1983	67% of Total load		53 s	5 h
Tokyo (Japan)	Jul 23, 1987	8200	2.8 million	20 min	75 min
US Western	Jul 2, 1996	11,850	2 million	36 s	A few minutes to several hrs
US Western	Aug 10, 1996	30,500	7.5 million	>6 min	A few minutes to 9 h
Brazil	Mar 11, 1999	25,000	75 million	30 s	30 min to 4 h
US Northeastern	Aug 14, 2003	61,800	50 million	>1 h	Up to 4 days
Denmark/Sweden	Sept 28, 2003	6550	4.85 million	7 min	Average 2–4.3 h
Italy	Sept 28, 2003	27,700	57 million	27 min	2.5–19.5 h
India	Jul 30, 2012	36,000	>300 million	NA	13.5 h
India	Jul 31, 2012	48,000	670 million	NA	2–8 h

Although blackouts have been the result of low probability events, most of these blackouts shared a common thread, which means that by employing better sensing and control techniques such failures could have been prevented or at least their effect could have been mitigated. It has been seen that many a times the blackout was the result of oversight by the operator or the equipment installed in detecting an otherwise manageable event. Ensuring required quality of power for the newly created digital society is another important aspect missed by the utilities. For the digital equipment, variations in voltage and frequency can be as catastrophic as a complete blackout [14].

The basic interconnected nature of power grid—with multiple benefits—is not likely to change. In order to mitigate the possible adverse impacts of this meshed nature of the grid, better monitoring and control mechanisms are required. The idea is not complete elimination of the probability of blackout rather to contain the possible faults in a restricted area. In addition, even if a major fault or a blackout occurs the system should be able to recover very quickly.

Therefore, in order to mitigate the adverse impacts of large-scale blackouts and power quality requirements for digital economy, the power grid has to be modernized.

Such a modernized form of power grid is termed as a “smart grid” [15]. The three basic features of a smart grid are enhanced monitoring and faster control, enhanced awareness toward potential problems, and intentional islanding in case of a disturbance in some section of the grid.

Apart from blackout, there are many other drivers for the development of a smart grid with enhanced monitoring, computation, and control using modern developments in these areas. Some of the important drivers are summarized below:

1. Deregulation of electricity market has resulted in unprecedented energy trading across many regional power grids. This arrangement has changed the basic nature of the power network presenting power flow scenarios and uncertainties for which the conventional grid is not suitable.
2. The increasing penetration of renewable energy will change the distribution system from a radial system to a meshed network resulting in a requirement for better monitoring and control. The intermittent nature of these renewable energy sources also presents a challenge due to the change in the power system dynamics.
3. The new age digital economy requires a power supply of high quality and high reliability.
4. As the networked nature of the power grid increases with an increase in the use of wide-area communications, the threat of physical and cyber attacks on the power grid introduces further complexity.
5. An important concern of the present times is the environment conservation and promoting sustainable growth. It requires making the power grid energy efficient, reducing peak demand, and maximizing the integration of renewable sources of electricity in the grid.

2.4 Smart Grid

The smart grid has not been defined in a formal way, but some features have been proposed in the literature. Based on these features, the smart grid is a power grid in which advanced sensing, control, and communication techniques are utilized. The smart grid is expected to be more efficient, stable, and flexible as compared to the conventional power grid [16–20]. Smart grid is envisaged as an upgraded version of the electric power grid, which is more reliable, versatile, secure, accommodating, resilient, and more useful to the consumers. Generally speaking, the vision of the smart grid includes [21]:

1. Optimal electricity delivery operations in the power grid.
2. Integrated use of information technology, including two-way communications at all the levels of the grid. The essence of this requirement is expressed by the phrase “using megabytes of data to move megawatts of energy” in a document of the Department of Energy, USA.

3. Facilitating the integration of renewable energy sources at a large scale.

The Electric Power Research Institute (EPRI), USA, has defined seven principal characteristics of a smart grid [22]:

1. Self-Healing in Nature

Self-healing ability of smart grid implies the grid is more aware of its operating state due to widespread real-time monitoring. In addition, the self-healing grid has the ability to island by isolating faulty elements from the rest of the system. The self-healing feature of the smart grid will result in increased reliability of service to consumers and help utility managers manage the electricity infrastructure in a better way.

2. Resilient to Threats

The smart grid will be resilient to disturbances, attacks; both physical and cyber threats, and natural disasters.

3. Involve Active Consumer Participation

Unlike the conventional grid, the consumers will participate actively in the smart grid. This active participation will help balance supply and demand and ensure reliability by modifying the way electricity is purchased and consumed. These changes will be the result of incentives for the consumers motivating for change in utilization pattern.

4. Provides Quality Power Suitable for the Digital Age

The smart grid will provide power supply of very high quality suitable for the present digital society. This will involve the use of real-time sensing and control techniques, enabling rapid diagnosis and solutions to events that impact power quality, such as switching surges, line faults, and harmonic sources.

5. Incorporates and Promotes the Use of Renewable Generation

High penetration of a large number of environment-friendly renewable energy sources at the distribution side will be an integral feature of the smart grid. The smart grid will not only accommodate these sources but their integration in the grid shall be promoted.

6. Interactive with Market

The smart grid shall create a better environment for the electricity trading market to thrive. Such a system will create an opportunity for consumers to choose among competing services. The smart grid is envisioned to provide the flexibility to utilities, regulatory bodies, and consumers to devise suitable working rules as per the requirement of a particular region.

7. Optimize the Assets

An important part of the smart grid vision is the use of modern technologies of monitoring and communication to optimize the use of its assets. The emphasis in the smart grid will be on condition-based maintenance of assets and not time based.

The US Congress has defined the smart grid as a power grid which includes [23]: (i) increased use of information controls; (ii) optimization of grid operations and resources; (iii) high penetration of renewable energy resources; (iv) implementation and promotion of demand response, energy efficiency measures, intelligent appliances, advanced electricity storage, load curve flattening technologies, advanced metering infrastructure, integrated communications, and distribution automation; (v) two-way communication between consumer and the utility for personalized control decisions; and (vi) allowing interoperability of appliances and equipment—through suitable standards—connected to the electric grid.

In Europe, the smart grid is described by the European Commission report as [24]:

1. Flexible because it fulfills the consumers expectation despite different changes and challenges.
2. Accessible in terms of allowing different distributed generation sources—especially renewables—with the grid.
3. Reliable in terms of security and power quality demands of the digital economy in the presence of disturbances and uncertainties.
4. Economical as it provides optimal value through innovation, energy efficiency measures, and regulation.

The smart grid research activities in China define the smart grid as a system that incorporates elements of conventional and modern power engineering, advanced sensing, computing and information technologies along with secure two-way communications for enhanced grid performance and a set of additional advanced services to consumers.

Based on the different characteristics of smart grid, [25] has proposed a working definition for the smart grid as follows:

> The smart grid is an advanced digital two-way power flow system capable of self-healing, and adaptive, resilient, and sustainable, with foresight for prediction under different uncertainties. It is equipped for interoperability with present and future standards of components, devices, and systems that are cyber secured against malicious attacks.

A comparison of the benefits offered by the smart grid over conventional grid is given in Table 2.2 [26].

2.5 Key Technologies for Smart Grid

As discussed in the previous sections, the smart grid will evolve from the conventional grid if some fundamental features are implemented in the grid. Implementation of these features requires the use of different technologies. The technological

Table 2.2 Comparison of conventional and smart grids

Characteristic	Conventional grid	Smart grid
Self-healing capability	The emphasis is on protecting assets after a fault so as to minimize the damage	The focus is on prevention of occurrence of fault and minimizing disruption of services to the larger area in case of fault
Consumer participation	Uninformed and non-participative consumer	Informed and actively involved consumers
Resilience to attacks	Vulnerable to natural and man-made threats	Resilient to cyber, physical attacks, and natural disasters; rapid restoration after a disturbance
Power quality for the twenty-first century digital economy	Power quality not fit for the digital appliances	Power quality suitable for digital economy is ensured
Integration of environment-friendly generation	Integration of renewable sources is not an integral part	Integration of distributed renewable energy sources is a fundamental part of the vision of smart grid
Communication	Generally absent or one way	Two-way communication at different levels of the grid
Asset maintenance	Time based	Condition-based with focus on prevention and minimizing impact on consumers

requirements for a smart grid have been classified into five groups by the National Energy Technology Laboratory (NETL). The identified groups are: integrated communications, sensing and measurement, advanced components and control methods, and improved interfaces and decision support [27]. Integrated communications are a critical requirement for implementation of functions like advanced meter reading. Advanced sensing and measurement is a fundamental requirement for making the grid more aware of its operating conditions. The information supplied by sensing and measurement devices should generally include measurement of power factor, power quality, phasor relationships, temperature, outages, power consumption profiles, etc. Considering the spread of power grid, these sensors must be of low cost and small size, with easy maintenance and security assured. Advanced components include power electronics like inverters for solar PV, superconducting cables, and electric vehicles. Advanced control methods depend on real-time measurements communicated through a dedicated and secure medium. Based on the collected data, the control center will analyze data, diagnose and take autonomous action whenever required. A brief description of various technologies expected to play a key role in the development of a smart grid is as follows [28].

2.5.1 Distributed Generation and Storage

Distributed generation is one of the most important technologies for the implementation of a smart grid. It is based on a widespread utilization of distributed energy resources, especially the environment-friendly renewable sources, in order to improve the power quality and reliability. In the conventional grid, distributed generation is mainly used as backup power and is not integrated to the grid. However, these renewable and green sources of electricity will be seamlessly integrated into the grid in smart grid. Apart from mitigating the environment impact of the conventional sources, this arrangement will also reduce the need for costly peaking infrastructure and can significantly reduce the probability of blackouts.

The basic concept of distributed generation is that the energy is generated and distributed through smaller generating systems closer the consumers. The advent of environment-friendly renewable sources of energy like wind turbines, solar photovoltaic cells, geothermal energy, and micro-hydropower plants has given a great impetus to the promotion of widespread usage of these technologies. Integration of environment-friendly distributed sources of energy is a fundamental aspect of the smart grid paradigm. Distributed generation offers significant benefits over the conventional power systems, as the costs associated with the transmission and distribution of power over long distances are reduced. Technologies have matured to such a scale that few kW to as much as hundreds of MW distributed generation plants are integrated with the power grid.

Integration of distributed generation not only reduces the operational cost but it offers certain benefits to grid planners also. Widely integrated DGs can reduce the peak demand, and hence, it offers an effective solution to the problem of high peak load shortages. It can also improve the reliability of the grid. Moreover, distributed generation offers an effective way for providing power to remote and inaccessible areas, especially in the developing countries. The generation systems used are usually small capacity systems and hence require lower gestation periods; it enables faster and easy capacity additions when required. Advancements in power electronics have ensured that these sources can be integrated seamlessly with the grid without major issues with maintenance of power, voltage, and frequency.

Distributed energy resources, especially renewable sources, are very important in achieving the desired characteristics of a smart grid. Their ability for power generation at the consumer site helps in reducing peak loads and hence better system management of the grid not only in terms of operation and control but also for better and economic planning. Implementation of net metering of grid-connected generation sources has made it possible that the consumers can export the excess electricity back to the grid. Therefore, in many cases the system planners are not required to invest in building new high voltage transmission lines to carry renewable power from conventional plants to distant towns and cities. Locally based solar, wind, biomass generators, fuel cells, and other distributed generation systems also offer benefits like reduction in power loss in long-distance transmission and improvement in voltage profile of consumers at the tail end of the distribution system.

With a network of distributed energy sources integrated with the grid, the islanding feature of smart grid can also be implemented. In island mode, it will be possible that a particular area is isolated from the grid without interruption during a disturbance. This feature is expected to play a crucial role in making the grid self-healing. The islanded area can automatically synchronize itself with the grid—in a seamless way—when it has returned to normal functioning.

At present, there are few challenges also to the integration of renewable energy sources at a large scale with the grid. The primary reason behind these concerns is that these energy sources are intermittent in nature, and hence, their effect on the grid dynamics is an area of concern. What are the effects of widespread renewable energy sources on power quality issues like harmonics frequency and voltage fluctuation, power fluctuation due to a sudden change in weather or seasonal changes in weather etc. are some of the issues on which the researchers are focusing [29].

2.5.2 Real-Time Monitoring and Control

The conventional power grid has a centralized generation and radial one-way distribution of both electricity and information. The lack of real-time monitoring leads to underutilization of the power network to avoid overloading. An extremely important requirement of smart grid is the real-time monitoring. If a large number of real-time monitoring sensors are deployed in the power grid, the existing power network can be utilized in a better way resulting in improved efficiency.

In the conventional grid, the consumer participation is at a minimal level, while in smart grid, the consumer is expected to be an active participant in the grid operations. It will require implementation of a secure two-way communication of information realized from real-time sensors deployed in the distribution system as well as the premises of the consumer.

The deployment of a massive number of sensors throughout the grid can improve its performance by better collection of useful information about a failure. It will also be helpful in postmortem analysis for creating a timeline of the sequence of events and suggesting remedial measures for preventing a repeat of the failure. An enhanced penetration of sensors in the grid will also enable a more effective detection of problems in their initial stages. These sensors are also required for the implementation of new functions in the grid like the demand-side management.

The application areas for sensors in the smart grid at all the three categories: end-user level, distribution level, and transmission level. The fast sampled information available from these sensors will facilitate rapid diagnosis and corrective action for the grid problems. The arrangement will also provide real-time display of state of components and the system performance over a wide area. It will help system operators in taking actions well before an impact on the larger area. The information from these sensors will also be helpful in the seamless integration of intermittent nature renewable energy resources.

2.5.3 Distributed Intelligence

Unlike the radial nature of a conventional grid, the smart grid will see two way and networked flow of electricity and information. Implementation of such an arrangement and its successful management requires a lot of decentralization and penetration of intelligence and control in all sides of the grid. This arrangement will help in monitoring the operating conditions of grid components and balance loads and resources dynamically to maximize energy efficiency and security in real time. The distributed intelligence will be implemented by appliances like smart meters and systems like geographic positioning system and mobile computing devices.

2.5.4 Integrated Communications

The essence of a smart grid is real-time monitoring and control which requires two-way communications. Fast, secure, and reliable two-way communication between different parts of the grid is an integral part of smart grid [28]. In the conventional grid, the communication infrastructure is available at a very limited scale. The use of communication is mostly restricted to non-critical requirements. Moreover, the system works in isolation at different levels in the grid. The smart grid vision requires an overall integrated approach for the implementation of communication system in the grid.

2.5.5 Demand-Side Management

Demand-side management (DSM) involves devising and implementing various activities—by the utility—which leads to desirable change in the load curve shape. The DSM activities basically influence the consumer behavior related to utilization of electricity in the consumer premises. DSM activities are supposed to be effective at the customer side in an economic way. Planning and operation level strategies both constitute the DSM activities. Simple action like exchanging old incandescent light bulbs by energy-efficient LED fixtures up to installing advanced metering infrastructure with load balance capability all comes under DSM paradigm.

A major driver for the concept of DSM has been the environment concern with the increasing use of electricity generated primarily through fossil fuels. In order to ensure sustainable growth, promotion of energy efficiency measures is imperative.

Depending on the domain of impact of the initiative on the customer side, DSM approaches can be categorized into the following.

(a) Energy efficiency.
(b) Time of use.
(c) Demand response.

Table 2.3 Smart grid technologies impact on the grid

Technology	
Automated meter reading	Lower operating cost, reduced power losses, enhanced reliability of electricity supply
Renewable energy	Reduced transmission losses, increased electricity supply
Distributed generation	Reduce transmission losses, increased electricity supply
Islanding	Enhanced reliability, reduced operating cost, increased electricity supply
Demand response	Reduced operating cost, reduced commercial losses
Demand-side management	Reduced operating cost, increased electricity supply

An illustrative example of the DSM technology is peak clipping. It is directed toward curtailing the peak load such that the need for costly infrastructure for peak load may be reduced. Reduction in the amount of peak load or the duration of the peak can be achieved by distributed generation and consumer participation by offering suitable incentives.

2.5.6 Demand Response

Another important technology for the realization of a smart grid is demand response (DR) . The conventional way of operating the power grid has been to continuously balance the supply against the load. The difficulties associated with large-scale storage of electricity are a major problem in the operation of grid. The demand on the power network also varies during the day with a small peak period of a few hours duration. An important concern for the grid operators and planners is to reduce the gap between peak load and base load to make the optimal use of power network. In other words, flattening of load curve is an important objective for the implementation of smart grid.

The DR initiatives are aimed at bringing the peak in the load curve down and delaying the construction of new power plants to serve the peak loads that occur for just a few hours. The value of DR lies in the flexibility offered at a relatively very low cost.

A summary of the smart grid technologies and their effect on the operation of power grid is given in Table 2.3

2.6 Important Requirements and Challenges for the Smart Grid

The smart grid requires implementation of various new technologies in the power grid. Enhanced monitoring through real-time sensors with high sampling rate and suitable communication network forms two essential requirements. The following sections describe some of the new technologies and their applications for realizing these goals. The implementation of these technologies in the power grid faces some challenges also. These challenges have also been discussed.

2.6.1 Sensing and Measurement in Smart Grid

Innovation in sensing and measurement is fundamental for the realization of a more aware and reliable smart grid. This objective can only be achieved by radically upgrading the sensing, measurement, and metering throughout the grid. The smart grid will have real-time measuring devices deployed across the power grid. These sensors will monitor the system and provide data to enable different online and offline applications. The measuring devices installed must be reliable and cost effective also. These sensors can play an important role in realizing a smart grid by:

- Collecting more information in a given time interval for analyzing the causes and restructuring the timeline of failure.
- Detecting the potential problems comparatively early thereby helping in the generation of a better corrective action.
- Detection of an external threat.
- Operating the grid in a more efficient way.
- Providing new services to the consumers like demand-side management.

2.6.2 Phasor Measurement Units

In its envisioned form, the smart grid encompasses all areas of power system: generation, transmission, and distribution. The underlying feature of the whole concept is enhanced—near real time—monitoring of the power grid and robust two-way communication infrastructure to transmit the monitored data and control action reliably and efficiently. Synchrophasors measurement has emerged as a technology which may be utilized to impart this essential feature of the smart grid.

A sinusoidal voltage or current waveform is generally represented by a complex number called phasor having magnitude and angle parts. When the measurement of phasors in a system is synchronized with the help of a precise time stamping technique, these phasors are referred to as synchrophasors. The device used for phasor measurement is called phasor measurement unit (PMU) . PMUs provide positive sequence bus voltage and associated branch current measurements with a high synchronization accuracy of 1 microsecond. The data available from PMUs is far better than the data available from remote terminal units (RTUs) in the conventional SCADA system. The installation of a large number of PMUs throughout the grid will result in better monitoring, faster control actions, state measurement, integration of renewables, etc. An important benefit is ease of postmortem analysis due to the availability of time-stamped data.

Integration of widely deployed PMUs with communication and advanced computations will help in monitoring the state of power grid in a better way. Better monitoring of state of the grid will make it more aware of its operating state, and hence, it will help in preventing blackouts. In the present SCADA-based system, the operator's action time is usually from few seconds to few minutes. However, due to high sampling rates of PMUs this time frame can be reduced to 100 ms. Phasor data concentrator (PDC) forms an important part of PMU-based measuring system. The role of a PDC is to gather data from the PMUs dedicated to it. The data received is then sorted out and time stamped considering the arrival of slowest data. This sorted and time-stamped data is then utilized for different control and analysis applications. This whole arrangement is commonly called a wide-area measurement system (WAMS) [30]. A general description of WAMS is shown by its constituent blocks in Fig. 2.2.

The availability of a suitable and secure communication infrastructure is vital for the implementation of WAMS. The amount of data generated and its subsequent utility makes selection of communication channel an important consideration for transmitting the PMU data. Because of their different nature and roles, the data from a single PMU and a PDC will require communication channels of different bandwidths [31]. General functions enabled by PMU data and the role of PDC are explained in Fig. 2.3.

Phasor measurement unit (PMU) is an electronic device that measures AC waveforms to provide the measurement of phasors. The phasor estimation is implemented by digital signal processing techniques taking into account the system frequency. These measurements are synchronized through global positioning system (GPS). The measured signals are sampled and processed by a recursive phasor algorithm to generate voltage and current phasors. The component blocks of a generalized PMU are shown in Fig. 2.4.

The PMU originated as a data recorder in 1991. Toward the end of the decade of 1990s, PMUs capable of real-time measurement were developed. The PMUs available at present are capable of sampling the data at the rate of about 6–60 samples per second. With reference to the dynamics present in the power grid, the lower end of the sampling rate can cater to dynamics between geographically different areas. The higher end of the sampling rate can represent local oscillations, generator shafts, and controller actions.

The phasor estimation algorithms used in PMUs fundamentally utilize the data samples over a preselected time window to estimate the phasors. Some estimation algorithms use a fixed value of frequency and calculate the magnitude and the angle of the phasor. Some advanced algorithms on the other hand estimate frequency and

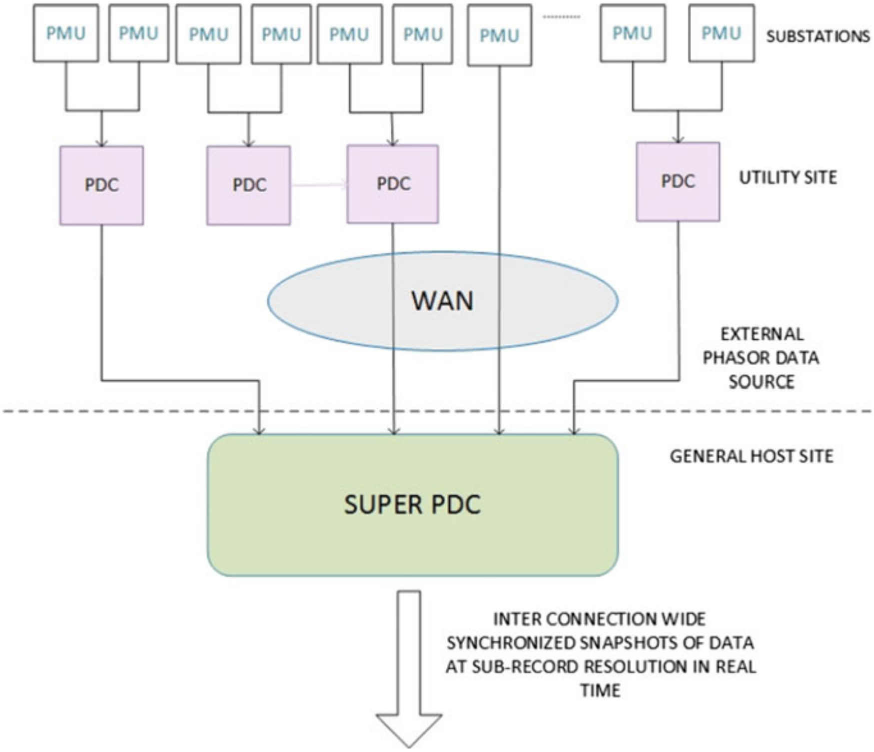

Fig. 2.2 Components of wide-area measurement system

rate of change of frequency in addition to the voltage and current phasors. Discrete Fourier transform is one of the most widely used phasor estimation techniques. Other commonly used methods are the Kalman filter or artificial neural networks.

2.6.3 Applications of PMU in Smart Grid

Widely distributed PMUs can provide accurate and synchronized measurement of current and voltage phasors in the power grid. It presents a radical change in the way grid has been monitored and controlled. Because of its benefits, PMU-based measurement presents one of the most important techniques for the implementation of a smart grid. Some of the potential benefits of the technology in the smart grid are [31]:

1. Preventing Blackouts
   As discussed in the initial sections, the underlying cause behind a blackout is a trivial event of low probability or a sequence of many such events. These

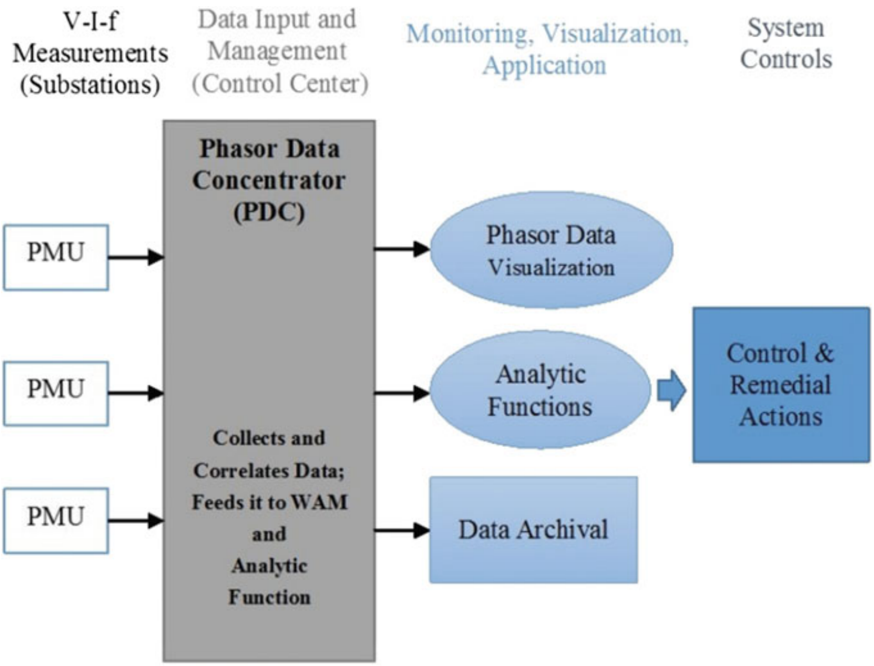

Fig. 2.3 Functions performed by PDC

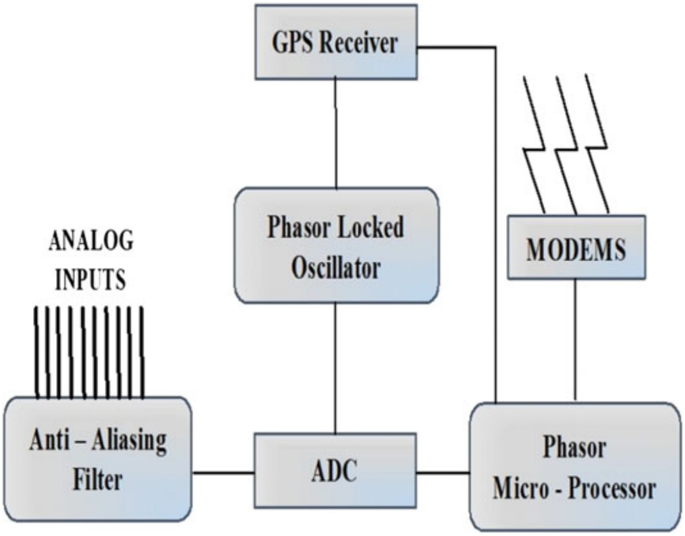

Fig. 2.4 Main components of a phasor measurement unit

blackouts cannot be completely eliminated, but their probability may be reduced by installing better monitoring, protection, and control systems. The accurate synchronization of measurements from PMUs can help in better protection of the system. This information will help in better real-time dynamic analysis for the prediction of change in different variables of interest. These improvements will lead to early detection of problems related to system security, identifying the possibility of disturbance, and generating corrective actions.

It has been seen from the history of blackouts that the postmortem analysis of fault is very difficult. An important obstacle has been the reconstruction of timeline of events leading to the failure. The measurements received from various sensors in the grid are not time stamped, and their sorting is a huge task. PMU data will be helpful in eliminating this problem. The GPS synchronization makes the recordings time stamped. The entire timeline of the disturbance can be reconstructed easily for postmortem analysis.

2. State Measurement

   The parameter set of voltage phasors at each bus of the power grid is known as “state” of the system. If the system state is known, it can be utilized along with the information of network topology to determine the operating status of the power system at a given instant. In conventional power grid, the measurement devices measure the magnitude only. The state estimator (SE) function utilizes the measurements of bus voltages, power injection, real and reactive power flows, etc., to estimate the state of the grid. State estimation is a nonlinear iterative optimization problem. For reliable state estimation, the observability condition must be satisfied. The observability condition requires redundancy in measurement.

   In addition to estimating the system state, the estimator carries out bad data detection. Bad data detection means detecting and eliminating gross errors in the measurement set. Another important function of the estimator is the detection of the topology errors in the network configuration.

   The development of phasor measurement unit can eliminate the problems associated with estimating the phase angle. The PMU measures voltage and current phasors synchronized through GPS. If a suitable number of PMUs are deployed satisfying the observability criterion, the state estimation can be converted to state measurement.

   The accuracy of the conventional state estimator is limited because the state is nonlinearly dependent on measurements, the measurements are mostly noise corrupted, and the solution of the linearized equation is iterative.

   Because of these inherent limitations, the state estimation is subjected to convergence issues reducing its accuracy and reliability.

   If a sufficient number of PMUs are installed in the network ensuring observability, the situation can be radically improved. In such a system, the relation between state and measurements will become linear and deterministic. The implementation of PMU-based state estimation has shown better accuracy, lesser time for computation, and improved redundancy [32].

3. Increasing the Transmission Line Capacity

An important aspect of smart grid is utilizing the existing power infrastructure in the best possible way. Utilizing technology for increasing the capacity of existing transmission lines is an important concern. The transmission capacity of a line is limited due to the electric and thermal limits on its loading.

In the conventional grid, the nominal transfer capability of a line is computed offline considering operational and environmental constraints. In the absence of any real-time monitoring, some additional conservative margins are set as a safety limit.

The PMU-based measurements providing synchronized data can be used for computing the transmission line capability in real time [33]. It creates the possibility of operating the lines with enhanced limits. In this way, better utilization of the existing infrastructure shall be ensured.

4. Calibration of Instrument Transformers

   In the monitoring of a power grid, the measurements from the secondary side of instrument transformers play an important role. However, ratio error and phase angle error present in the instrument transformers limit the accuracy of measurement.

   Therefore, for effective utilization of these measurements it is necessary that the calibration of instrument transformers is proper. The availability of accurate, time-synchronized phasor measurements available at a high sampling rate has the potential of ensuring accurate calibration of the instrument transformers [33].

5. Integration of Renewable Resources

   The electricity demand has been increasing consistently around the world for some time. The generation of electricity being mostly through non-renewable and polluting sources has raised serious concerns for the environment. These concerns have led to a huge push toward promotion of environment-friendly renewable sources of electricity like solar and wind. Integration of these clean and green sources of electricity is an important part of the smart grid.

   The inherent intermittent nature of these sources presents a challenge to the grid operators. As the penetration of these sources is growing rapidly, a situation will arrive when the inverter-based generation in the grid will be comparable to the conventional electromechanical generation. This situation will completely alter the dynamics of the power grid [34]. The conventional SCADA-based monitoring system may prove inadequate for such a scenario.

   Measurement of synchrophasors by PMUs with their high accuracy and GPS synchronization can prove useful in this case. The dynamic snapshot of wide area provided by the PMUs will be helpful in better monitoring the grid integrated with large-scale solar and wind generation.

   Large-scale penetration of solar PV plants will change the distribution system completely as many consumers will also act as producers of energy for at least sometime in the day. Such a two-way flow of electricity will be completely new for the distribution system basically designed as a radial network. Development of specially designed PMUs for distribution side is also a potentially beneficial possibility [35].

6. PMUs in Distribution System

Another important part of the smart grid vision is restructuring of the whole distribution system and its operation. In fact traditionally, the distribution side of a power grid has been the most neglected part of the system with little or no automation, despite the fact that most of the power grid blackouts have been rooted in the distribution side [36]. The technologies to be introduced in the distribution side of smart grid are: distribution automation (DA), advanced metering infrastructure (AMI) , and demand response (DR) . DA involves utilizing real-time information from sensors and meters for fault location, automatic reconfiguration of feeders, voltage and reactive power optimization, and control of distributed generation [37]. AMI is another important component of the smart grid infrastructure, and it includes smart meters and home automation networks. Its main function is to involve the user, allowing the system to establish an online connection with the consumer and providing the consumers some amount of control. DR is another key feature of smart grid, and it may be defined as 'changes in electric use by the consumers from their normal consumption patterns in response to changes in the price of electricity or some other incentives'. The primary objective behind these measures is to induce lower electricity usage at times of peak load [38].
Accurate real-time monitoring and reliable communication of the monitored information is an integral part of all the above-mentioned technologies. Recently, the attention of researchers has turned to the use of deployment of PMUs in the distribution system to serve this purpose. The main motivating factors behind this are: (i) declining cost of PMU hardware and (ii) the availability of required communication infrastructure as a part of AMI [39].

A brief account of the possible benefits of PMU deployment at the distribution level and review of related literature is as follows [40, 41]:

1. Distribution State Estimation
   One of the most important benefits of PMU placement in the distribution system is the ability to correctly determine the system state using distribution state estimation (DSE) based on time-stamped data received from the PMUs. DSE will result in better visualization, control, and optimization of resources. The results of DSE may also be utilized for implementing DR technology, topology estimation, and as error checking tool for the transmission system state estimator at the substation gateway [42]. The effectiveness of incorporating the phasor measurements was demonstrated by assuming different number of PMUs available in the system. Results show that the accuracy of DSE substantially increases with the increase in number of PMUs.
2. Distributed Generation
   Another important aspect of the distribution system in smart grid is distributed generation (DG). DG implies that in addition to provision of central generating stations of a conventional power grid, the smart grid will utilize small generating units distributed on the distribution side near the consumers. These DG sources are supposed to be clean renewable sources of electrical energy. This arrangement will result in reduction in the transmission losses and reduced emission of CO_2, detrimental to the environment. However, penetration of DG in the grid will

completely alter its dynamics as the renewable sources are intermittent in nature depending upon weather conditions. It necessitates tools for better monitoring of the distribution system. Reference [43] presented the effectiveness of distribution state estimation assisted by the PMU data. A distributed system was simulated with the presence of a wind power source, and DSE was performed without and with PMU. Results reflected an improvement in the DSE performance although only magnitude value was taken from the PMU.

3. Stability Analysis and Monitoring
   Owing to a growing penetration of distributed generation in the grid, stability may be adversely affected. The use of electric vehicles is also growing presenting another challenge to the system stability because of their fast-changing dynamics. With the help of fast and accurate measurement from PMUs better monitoring of distribution systems in the presence of these challenges may be implemented. These measurements will be helpful under normal and faulty conditions [44].
   It is also expected that as the distribution system becomes more dynamic and meshed, distribution level PMUs will also help in providing useful information about the transmission side [45]. A voltage instability indicator using PMUs in distribution system has been presented in [46]. The instability detector was tested on two different power networks, and it gave satisfactory results.
4. PMUs in Controlled Islanding
   Power grid is a complex integrated network experiencing a large number of dynamic phenomena all the time. Due to its interconnected nature, a fault in any part of the network may propagate and other parts may experience unstable operation. Under this scenario, it becomes very difficult to maintain normal operation of the integrated network. Any such effort may result in shutdown of major part or even the whole system, commonly known as blackout. Splitting a large power network into smaller subsystems may limit the propagation of a fault in the network. The enquiry committee, which investigated the Indian grid blackouts, recommended that controlled islanding should be implemented in the grid in case of a major fault. Separating the faulty part from the other parts of the grid will help in containing the fault. These small self-sufficient subsystems are called islands of the system, and this approach is known as controlled or intentional islanding [47, 48]. This intentional islanding restricts the propagation of disturbance from weak or unstable parts to stable parts of the system. After execution of islanding although the system will be operating in a degraded state, the customers will continue to be served [49]. Analysis of major blackouts in the world and simulation studies on some of the blackouts provide sufficient evidence that if proper islanding followed by load shedding had been performed in time then some of these blackouts may have been prevented. Moreover, it is easier to control small subsystems and this arrangement also helps in quick restoration of the system.
   In order to maintain integrity of individual islands, static and dynamic stability of each island should be maintained. An islanding scheme satisfying this requirement is termed as proper islanding. A proper islanding scheme should satisfy the following constraints [50]:

(a) *Integrity Constraint*: There should be interconnection between all the buses inside an island.
(b) *Synchronization Constraint*: All the generators in an island should be synchronized.
(c) *Power Balance Constraint*: This constraint requires that the power generated by the generators in a particular island should be almost equal to the total load in the island.
(d) *Line Limit Constraint*: The transmission lines should not be loaded above their thermal and steady-state limits.

For implementing controlled islanding, the following tasks are to be carried out in a sequential way:

(a) Recognizing the critical instant for intentional islanding. Criticality implies that islanding is inevitable; otherwise, the system will collapse leading to blackout.
(b) Identifying proper islands for network separation such that each island is sustainable in terms of power balance and stability.
(c) Implementation of the islanding scheme in such a way that possibility of any large oscillation and instability in the islands is avoided.

Therefore, an important consideration in intentional islanding is identifying the instant at which the intentional islanding must be implemented. Synchronized measurements available from PMUs widely deployed in the power grid can be used for assessing the system state and taking the decision for intentional islanding. Another application of PMUs in islanding is the utility of these units in maintaining the observability of individual islands.

In order to ensure that the islands created are sustainable, the islanding scheme should result in at least one generator and one load in each island. The observability of all the islands shall be maintained after intentional islanding. The power balance constraint in all the islands has to be satisfied.

2.7 Communication Requirement

An important and integral requirement of the vision of smart grid is a reliable real-time flow of information between different components of the grid. Therefore, a dedicated and secure communication medium is mandatory for the implementation of a smart grid. In the conventional power grid, only a limited communication infrastructure is involved because there are only a few sensors installed in the grid. Moreover, the information these sensors are supposed to transmit is mostly non-real time. However as discussed in the previous section, the smart grid will involve a massive deployment of sensors at different levels in the grid. In order to handle such a vast amount of data flow, a reliable and robust communication infrastructure is required in the smart grid.

Apart from improving the monitoring and control in the power grid, communication infrastructure is required to support many new but characteristic features of the smart grid. Flow of information from home appliances to smart meters and communication between smart meters and data concentration centers are some of the examples of such applications.

2.7.1 Challenges in Communication Systems for Smart Grid Application

The implementation of a smart grid in true sense will require a supporting suitable communication system. The communication system in smart grid will be a complex system because of the two-way communication to be implemented at most of the levels. In addition, the utilization of appliances like smart meters is also dependent on communication system. Transmission of a huge amount of data generated at a very fast rate from PMUs is also a challenge in the smart grid.

Such a complex communication system will face several problems that need to be solved in order to establish reliable and robust communication. Some of these problems are discussed below.

Interference

Smart meter deployment in the consumers' premises is an integral part of the smart grid. At present, there are many electrical and electronic devices in a typical household and their number is increasing each day. A home area network (HAN) is a reality in modern homes. This dense deployment can cause interference between the home area networks and the smart meter. It can also result in transmission of unreliable signals from smart meters compromising the security of the whole system.

Interference with the communication system in the smart grid can also be caused by harmonics emanating from the power lines.

Data Transmission Rate

The communication system in smart grid is a crucial necessity for data acquisition, analysis, and conveying control actions to the components and devices of the smart grid. However, deployment of a massive number of smart meters and real-time sensors as required in the smart grid will generate a huge amount of data that has to be transmitted in a timely and secure manner. Moreover, the requirement of two-way communication has also to be satisfied. Therefore, communication media transferring huge amount of data in a secure and fast way is a fundamental requirement for the smart grid.

Standardization

The power grid has a variety of components. The smart grid requires two-way communication among many of these diverse components as an integral part of the grid. The implementation of such a system requires integrated communication system.

Efforts are ongoing all over the world for developing suitable protocols and standardization. Organizations like the IEEE, European Committee for Standardization, American National Standards Institute, International Telecommunication Union are involved in these efforts.

2.7.2 Cyber Security

As discussed in the previous sections, the smart grid will mainly function through a communication network carrying signals about monitored variables from real-time sensors and control actions. Transfer of a large amount of critical information makes the communication system prone to intrusion and possible subversion. The risk is much greater in case the communication system is a shared medium. For example, the hackers can manipulate billing system causing financial losses to the company by intercepting the data between smart meters and utility.

The intruders can also manipulate the data being sent from the control center resulting in wrong decisions threatening the whole system. Important smart grid components like PMUs, PDCs are dependent on secure communication and prone to cyber attack.

Apart from these issues, any problem in ensuring reliable communication can cause problems to the other components like PMUs. The communication medium implemented should be able to handle these challenges. However, the security measures adopted should not affect the desired operations of the other components. For example, the measurements from PMUs are time sensitive. These measurements should reach the data collection center within about two seconds. It is imperative that any security measure applied should not cause a time delay.

The interdependence of modern and sophisticated technologies in the smart grid is another concern. PMU data is based on the global positioning system for synchronization of the measurement. Therefore, the accuracy and utility of the measurements can be compromised if the GPS is jammed or spoofed. Such a scenario will result in an error in the time stamping of the PMU data making the measurements useless.

2.8 Evaluating the Smart Grid Progress

The utilities are working toward realizing a smart grid. There is a need to make these efforts concerted and organized. Some roadmap, benchmarks, and deliverables are also to be defined for self-assessment during the transition. Some efforts have been made in this direction also. The Smart Grid Maturity Model (SGMM) [51] is one such initiative. SGMM presents an organized approach that can be utilized to create an action plan of activities, finances, and necessary initiatives in making the power grid smart.

Table 2.4 Five levels of Smart Grid Maturity Model [51]

Level	Description	Result
Level 1	Wants to transform the grid as smart grid. Analyzing the techno-economic feasibility	Vision
Level 2	Business case studies have been done, and the decision for transition is taken but clarity in the path to transition is lacking	Strategy
Level 3	Smart grid functionality is added at various levels. Tangible benefits are seen	Systemization
Level 4	System-level implementation of smart grid achieved. The enhanced monitoring and control of smart grid vision is in place	Transformation
Level 5	Sharing the knowledge and experience gained in the implementation of smart grid. Exploring areas for further improvement	Perpetual innovation

The SGMM was developed by IBM in collaboration with the Global Intelligent Utility Network Coalition. The initiative was also supported by the American Productivity and Quality Center.

The SGMM proposed five levels: Level 1 to Level 5. Depending on their present status and future requirements, a utility or organization can identify which level is optimal for their smart grid vision. Table 2.4 provides a description of the five levels of SGMM.

2.8.1 Worldwide Developments

Developing the smart grid and its enabling technologies has become a cornerstone for all the developed nations and major developing nations like China and India. A brief account of smart grid development activities in some countries of the world is as follows.

2.8.2 USA

Efforts for modernizing the power grid in the USA gained momentum from the beginning of the twenty-first century. Different phrases and terms have been used for a modernized and future grid like "Intelligrid" by the US Electric Power Research Institution. In 2003, the Department of Energy (DOE) released a plan for the smart grid of the future and accordingly named it "Grid2030". In 2004, the "GridWise" project was launched detailing the "National Transmission Technology Roadmap".

An important development for the smart grid was "Energy Independence and Security Act (EISA)" of 2007. An important study on smart grid standards and interoperability principles was released on 2009. The study is entitled "IEEEP2030", and it is believed to be the formal beginning of the development of smart grid in the country [52].

North American SynchroPhasor Initiative (NASPI) is also an important development toward the research work on the technologies required for the implementation of a smart grid. It has been seen in the previous sections that the synchrophasors measurement available from widespread PMUs will play a critical role in the development of a smart grid. NASPI is a consortium of the electric industry, the North American Electric Reliability Corporation (NERC), and the US Department of Energy (DOE) to advance the use of synchrophasors technology for wide-area measurement, monitoring, and control.

The objective of NASPI is to provide a data bank of synchrophasors measurement for analysis and research applications. A large number of PMUs, PDCs, and high-speed secure communication medium have been installed for obtaining the PMU measurements and their effective utilization.

2.8.3 European Smart Grid

Realizing the need for a reliable, energy-efficient, and environment-friendly power network, efforts have been underway in the Europe also. Installation of smart meters on a large scale, integration of high level of renewable energy sources, and implementation of a competitive deregulated power market are important initiatives in this direction.

Three main challenges were identified by the European Electric Grids Initiative (EEGI) for the transition to a smart grid. These challenges are the integration of new generation sources and innovative management of consumption, better planning and management of the grid, and new market paradigms to achieve maximum benefits for the people [53].

2.8.4 Chinese Smart Grid

Development of smart grid began in China in the year 2007 with the feasibility study by East China Power Grid Corporation. The study report proposed the development of smart grid in three stages. The first phase during the years 2009–11 was supposed to be devoted for planning the pilot stage and shall involve research for the development of key technologies and their trial. The second stage is called comprehensive construction phase targeted during 2011–2015. This phase involved control and integration and achieving major breakthroughs in the development of technologies and components. The third and final stages will be the upgrade stage during 2016–2020, and it is proposed that a unified smart grid shall be operational at the end of this stage [54].

2.8.5 Indian Smart Grid

Addressing the multiple issues of inadequate resources, poor reliability, and poor power quality in the Indian grid, Indian Electricity Act was enacted in 2003. The measures recommended in the act were primarily aimed at modernizing the distribution system. Initiatives like accelerated power development and reform programs were important follow-up actions on the act.

The development of smart grid technologies has been identified by the utilities and the policy makers as an important opportunity for making the national grid robust, self-healing, participative, and economic [55]. Government and utility efforts are underway for the utilization of modern sensing, computation, and control techniques in the power grid. The main focus of the smart grid initiatives in the Indian grid is in the following areas: distribution automation, renewable integration, improved reliability, interoperability, and substation automation. The concerned ministry approved a vision and roadmap for the smart grid in 2013. The project has been taken up as National Smart Grid Mission [56].

As a part of the mission, the government is promoting the installation of smart meters, support to electric vehicles, substation modernization, promotion of rooftop solar PV, and deployment of advance monitoring devices in the grid.

The projected growth in electricity demand and the adverse impact on environment is a concern for the government. To address this concern, the government has set up a target of the installation of 175 GW of cumulative capacity from renewables by the year 2022. Integration of renewable sources of electricity at this huge level will move the Indian grid closer to its smart grid vision. However, it will also bring certain operational challenges which need to be addressed.

Some of the other major efforts in India toward achieving a smart national grid are as follows.

Indian Smart Grid Task Force (iSGTF)

The Indian Smart Grid Task Force (iSGTF) [57] was constituted to (i) promote awareness and coordinate various smart grid efforts in India, (ii) promote research and development of smart grid technologies and components, and (iii) work on seamless integration by developing standards and interoperability.

Five groups have been formed under the task force for the following: (i) studies and pilot projects on new technologies, (ii) reduction of losses and theft, (iii) provide power to remote areas, (iv) renewables integration, and (v) ensure physical and cyber security of the power network.

Indian Smart Grid Forum (ISGF)

The implementation of a smart grid requires coordinated efforts from industry and utilities. Keeping in view this requirement, the Indian Smart Grid Forum [58] was established. The mandate of this forum includes working in collaboration with iSGTF on devising technology, regulations, policy, and pilot programs.

PMU Installation Initiatives

The Indian power grid used to function as five regional grids in the past. In the year 2013, the regional grids were synchronized to make a national grid. The national grid—considering the geographical span—is a highly complicated network experiencing inter-region power flows. Wide-area monitoring using PMUs can play an important role in monitoring the grid. Recognizing this potential, a pilot project on PMU-based measurements was taken up in India.

Four PMUs have been installed in the North Indian region at selected substations. The data generated by these PMUs is reported to the PDC installed at Load Dispatch Centre of North India. Encouraged by the success of the PMU pilot project, the state utility Power Grid Corporation of India has been increasing the number of PMUs in the Indian grid. As a part of the vision of smart grid in India, it is planned that sufficient number of PMUs shall be installed in a phased manner to implement Real Time Dynamic State Measurement System [59].

The benefits of the installation of PMUs in the Indian grid are already visible. The availability of GPS-synchronized measurement of phasors has greatly increased the visibility of the control operators in the grid. It has been found that many events have been detected by the operators through PMU data which would have gone unnoticed by the conventional system. Many dynamic events have been analyzed in the Indian grid after PMU installation. Sometimes, the PMU data helps the operator in identifying and locating an area of interest. Then, the operators can look for the details in the SCADA [60].

At present, the use of PMU data is mostly restricted to offline mode only. However, the benefits realized are a cause for encouragement for the utility. The implementation of state measurement system based on PMUs will completely change the way the Indian grid has been monitored. Realizing the important role PMUs are going to play, a PMU test facility has also been established. The facility is available at the Central Power Research Institute (CPRI). PMUs to be utilized for measurement and protection can be tested with reference to the standards for static and dynamic conditions [61].

The implementation of automatic metering infrastructure is also taken up in India at a large scale. A detailed description of these projects is available in [62]. About

14 pilot projects have been initiated in the Indian grid. Most of these pilot projects are in the area of distribution and implementation of AMI in the grid. One such pilot project has been done at Puducherry. The techno-commercial analysis of the project shows that it has been successful in promoting the smart grid concept [63].

2.8.6 Conclusion

The power grid represents an excellent engineering innovation for the modern world. The grid in its present form has been largely responsible for making the electric supply a major driver for growth. However, with the ever-expanding grid and additional challenges like higher power quality and environmental concerns, the grid faces difficult times. The need of the hour is to utilize the recent developments in sensing, communication, and control for making the grid more resilient and environment friendly. The vision of smart grid is to make the power grid more aware of its operating conditions, self-healing, and accommodating the renewable energy sources. In the smart grid, the consumer is also expected to play a more participatory role. The implementation of real-time measurement, distributed intelligence, and two-way communication will surely lead the power grid toward a smart grid. There are challenges related to the development of sensors, handling of large amount of data, and ensuring secure and reliable communication in achieving this objective. These challenges are to be addressed by academia, industry, utility, and policy makers for the realization of a smart grid.

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