Review Article

Challenges in the Smart Grid Applications: An Overview

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The smart grid is expected to revolutionize existing electrical grid by allowing two-way communications to improve efficiency, reliability, economics, and sustainability of the generation, transmission, and distribution of electrical power. However, issues associated with communication and management must be addressed before full benefits of the smart grid can be achieved. Furthermore, how to maximize the use of network resources and available power, how to ensure reliability and security, and how to provide self-healing capability need to be considered in the design of smart grids. In this paper, some features of the smart grid have been discussed such as communications, demand response, and security. Microgrids and issues with integration of distributed energy sources are also considered.

1. Introduction

The traditional electrical power grid is unidirectional in nature, where the electricity flows from power generation facilities to end users. This system has served well for the last hundred years. Recently, however, it has been subjected to government deregulation and has suffered from several technical, economic, and environmental issues. Modern society demands this system to be more reliable, scalable, and manageable while also being cost effective, secure, and interoperable [1]. The next-generation electric power system, known as the "smart grid" [2], is a promising solution to the long-term industry evolution. The smart grid is expected to revolutionize electricity generation, transmission, and distribution by allowing two-way flows for both electrical power and information [3]. Moreover, it can complement the current electric grid system by including renewable energy resources, such as wind, solar, and biomass, which is environmentally cleaner as compared to the fossil fuels used in many bulk electric power generation facilities. Furthermore, each of these new power generating systems can be relatively small and can be distributed around the load centers to increase the reliability and reduce the transmission loss, which adds another degree of flexibility while also increasing the complexity to the current power system.

The definition and description of the smart grid are not necessarily unique, as its vision to the stakeholders and the technological complexities can be different [4]. For example, the Ontario Smart Grid Forum has defined the smart grid as follows.

"A smart grid is a modern electric system. It uses communications, sensors, automation and computers to improve the flexibility, security, reliability, efficiency, and safety of the electricity system. It offers consumers increased choice by facilitating opportunities to control their electricity use and respond to electricity price changes by adjusting their consumption. A smart grid includes diverse and dispersed energy resources and accommodates electric vehicle charging. It facilitates connection and integrated operation. In short, it brings all elements of the electricity system production, delivery and consumption closer together to improve overall system operation for the benefit of consumers and the environment" [5].

The U.S. Department of Energy (DOE) has suggested the definition of smart grid as follows.
“An automated, widely distributed energy delivery network, the Smart Grid will be characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer preferences to individual appliances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level” [6].

Based on the common themes (which are “communication, integration, and automation that is sustainable, economic, and secure” [4]) of the definitions and descriptions of the smart grid from different organizations, Canadian Electricity Association has defined smart grid as follows.

“The smart grid is a suite of information based applications made possible by increased automation of the electricity grid, as well as the underlying automation itself; this suite of technologies integrates the behaviour and actions of all connected supplies and loads through dispersed communication capabilities to deliver sustainable, economic and secure power supplies” [4].

In general, a smart grid is the combination of a traditional distribution network and a two-way communication network for sensing, monitoring, and dispersion of information on energy consumptions. An example of communication architecture in a smart grid is shown in Figure 1. A typical smart grid consists of numerous power generating entities and power consuming entities, all connected through a network. The generators feed the energy into the grid and consumers draw energy from the grid. The ad hoc, dynamic and decentralized energy distribution are hallmarks of the smart grid.

It is expected that employing two-way communications in the smart grid will not only allow dynamic monitoring of the use of electricity but also open up possibilities of automated scheduling of electricity use [3]. The benefits of the smart grid, as summarized by the US DOE, include “(1) improved reliability; (2) increased physical, operational, and cyber security and resilience against attack or natural disasters; (3) ease of repair, particularly remote repair; (4) increased information available to consumers regarding their energy use; (5) increased energy efficiency along with the environmental benefits gained by such efficiency; (6) the integration of a greater percentage of renewable energy sources, which can be inherently unpredictable in nature; (7) the integration of plug-in electric vehicles; and, (8) a reduction in peak demand” [3].

An essential feature of a smart grid is the use of information and communications technology to gather and act on information in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production, transmission, and distribution of electricity [7]. In Section 2, some aspects of communications in smart grids will be reviewed.

One main component of the smart grid is the possibility of customer participation in the overall grid energy management. This participation is done via the notion of demand response or demand side management, in which (a) the power company provides incentives for customers to shift their load over time, and (b) customers are provided with partial autonomy to participate in buying/selling energy from/to the grid. Thus, in any smart grid mechanism, it is imperative to factor in demand response models and their associated challenge. In Section 3, a discussion of demand response and the state-of-the-art contributions are provided.

Recent technological advancement on distributed energy resources management helped creating a new grid paradigm, the smart microgrid distribution network [8]. A microgrid is an electrical energy distribution network that includes a cluster of loads, distributed generators (e.g., renewable energy sources such as solar panels and wind turbines), transmission, and energy storage systems. A microgrid can dynamically respond to the changes in energy supply by self-adjusting the demand and generation [9]. Controlled and reliable integrations of distributed energy resources and microgrids are extremely important to ensure an uninterrupted power supply.
supply in the most efficient and economic configuration. In Section 4, several aspects of the microgrid and integration of distributed energy sources will be reviewed.

In addition to the most effective use of network resources and available power, the requirements of reliability and security are also important considerations in the design of smart grids [2]. In Section 5, security aspects of the smart grid will be reviewed.

2. Communications in Smart Grid

The automated and distributed energy system delivered by the smart grid largely relies on two-way flow of electricity and two-way flow of information [10]. Almost instantaneous balance of supply and demand at the device level in a smart grid is possible due to the incorporation of distributed computing and communications which enables exchange of information in real time [10]. In a report by the Electric Power Research Institute (EPRI) to the National Institute of Standards and Technology (NIST), communications in the smart grid are emphasized as follows.

"Communications between each component in the smart grid is extremely important to maximize the use of available electrical power in a reliable and cost effective way. Therefore, how to efficiently manage the new, intelligent power system and integrate it into the existing system has become one of the main challenges for the smart grid infrastructure" [10].

The smart grid, being a vast system, may utilize various communications and networking technologies with its applications, which include both wired (e.g., copper cable, fiber optic cable, and power line carrier) and wireless communications (e.g., cellular, satellite, microwave, and WiMAX). Short range wireless communication technologies such as WiFi and ZigBee can also be used in some smart grid applications, such as in home area networks [10]. The US DOE has classified smart grid applications into six functional categories: (i) advanced metering infrastructure; (ii) demand response; (iii) wide-area situational awareness; (iv) distributed energy resources and storage; (v) electric transportation; and (vi) distribution grid management [3]. Some of the communications and networking technologies can be used with multiple applications [3].

One of the applications area in smart grid communication is the so-called Advanced Metering Infrastructure (AMI). Unlike the traditional way, where technicians are sent to each consumer site monthly to record the data manually for the billing purpose, the smart meters in AMI provide real-time monitoring capability of electric loads remotely. The information on power usage can be collected periodically (e.g., every 15 minutes) by a data concentrator at the intermediate layer using wired or wireless communications and be forwarded to a central location. The real-time data is efficient and precise. This allows utility companies to analyze consumer energy consumption data and to provide outage notification and billing information using two-way communications [3]. Furthermore, through AMI, consumers can be provided with historical data for energy consumption and dynamic pricing, as well as suggestion to reduce peak load. This will encourage participation and response of the end users in energy management. For example, a customer can adjust the power usage based on the detailed energy consumption information and the dynamic peak price, which can be displayed on some in-home display (IHD) units. Analysis of data also helps utility companies to better understand the pattern of consumer power consumption and to plan for reducing some of their financial burdens [11].

In the context of home and office applications of AMI, the utility network would have four tiers: (i) the backbone which is the path to utility data center (ii) the backbone, which is the aggregation point for neighborhood data (iii) the access point, which is most likely the smart meter, and (iv) the home area network (HAN) [3]. The HAN is envisioned to connect the smart meters, smart appliances, electric vehicles, and electricity generators and storage units. The idea here is to incorporate data communication for HHDs and load controls for automated energy management during peak hours. Normally, each device in the HAN will transfer data indicating its instantaneous electricity use; therefore, communications needs can be considered as modest [3]. However, any communication technology selected for this application should be scalable to meet the requirement of large home and office buildings. It is noted in [3] that, other than demand response and distributed generation, the reliability requirements for in-home applications are not extremely critical (e.g., ranged from 99 percent to 99.99%), and so is the latency requirement (e.g., ideally between 2 and 15 seconds). Reasonable timeliness is still required though for consumers awareness and for any upstream applications, such as demand response that depends on this information [3].

For communications, low-powered, short-distance technologies have been investigated for on-premises applications that include wireless communications, such as WiFi (based on IEEE 802.11 standard) and ZigBee (based on IEEE 802.15.4 standard), as well as powerline networking such as HomePlug that uses existing electrical wiring in the home to carry data [3]. Although there is no general consensus yet on a standard, ZigBee, followed by HomePlug, appears to be promising technology for these applications. ZigBee, being wireless, offers several advantages [3] and expected to effectively communicate and control various smart appliances in home. HAN may also open up the possibilities of remote home monitoring and control, such as a thermostat or an appliance, through smart phones [3].

Once the HAN devices communicate data to the smart meter, this information should be carried to an aggregation point, often is a substation, a pole-mounted device, or a communication tower [3]. The bandwidth, reliability, and latency requirements for this application can be similar to that of in-home networking. Traditionally, power line carrier (PLC) technology has been used, which is usually low cost; however, it offers a very low bandwidth and also requires hopping around transformers [3]. To address this issue, many current AMI deployments have used wireless mesh networks for this application. Furthermore, it has been commented in [3] that "traditional PLC and wireless mesh may well be replaced by broadband communications such as the IEEE 802.16e mobile WiMAX standard, broadband PLC or next-generation cellular technologies" [3].
Information from aggregation points to the utility is transferred over the backhaul, which is typically a private network. Several technologies that have been employed include optical fiber, T1, and microwave. To transfer data from the hub to the utility, commercial wireless connectivity can also be used. As compared to HAN and aggregation points, a backhaul network likely requires lower latency and relatively higher bandwidth [3]. A detailed discussion on AMI and communication requirements for other smart grid applications (i.e., demand response, wide-area situational awareness, distributed energy resources and storage, electric transportation, and distribution grid management) can be found in [3].

In general, communication infrastructure for smart grid should meet requirements for time synchronization, reliability, latency, criticality of data delivery, and support for multicast [2]. Furthermore, a major issue in networking communications in smart grid is interoperability. Standardization of smart grid communication has received significant attention. A number of organizations that are working on this include IEEE, International Electrotechnical Commission (IEC), and the National Institute of Standards and Technology (NIST). Several relevant standards from these organization are listed in [2], which can be summarized as follows.

(i) **IEEE.** IEEE defined standards include IEEE C37.1 (describes requirements of SCADA and automation systems); IEEE 1379 (on communications and interoperations of intelligent electronic devices and remote terminal units in substations); IEEE 1547 (specifies the electric interconnection of distributed resources); and IEEE 1646 (on communication delivery time for substations) [2].

(ii) **IEC.** IEC defined standards include IEC 60870 (defines communication systems for power system control and specifies requirements for power system inter-operability and performance); IEC 61850 (defines automated control related to substation management); IEC 61968 and IEC 61970 (on model for data exchange between devices and networks); and IEC 62351 (on cyber security of the IEC protocols) [2].

(iii) **NIST.** NIST published standards include NIST 1108 (describes, among others, smart grid inter-operability and requirement of communication networks); and NIST 7628 (describes smart grid information security issues) [2].

Researchers are also diligent in investigating the impacts and issues in smart grids. For example, in [11], the authors have surveyed on the use of the smart metering system and in-home displays in residential environments of two different sized cities in Korea. The survey results have indicated that, by knowing the real-time feedback of power consumption, the reduction in energy consumption can be up to 10% during the winter season [11].

Optimal power flow (OPF) formulation is a popular tool for minimizing the generation and operation costs in power system. Bruno et al. [12] have adopted this approach to address load control problem in distribution grids, with an objective of reducing the overall costs of an energy distribution company. Lewis et al. [13] have summarized communication methods for smart metering, based on both wired and wireless communications. In their opinion, the powerline communication (PLC) is an ideal option for data transmission between smart meters and the data concentrator due to the requirement of low cost, low bit-rate communications. A new code scheme is presented in [13] for orthogonal frequency-division multiplexing (OFDM) based PLC system against time varying noise.

Singh and Vara [14] have applied smart metering technology in grid computing for optimizing the energy usage of data centers. They have introduced a new architecture to incorporate the smart grid with the conventional grid computing system, where various meters, deployed in data centers, can provide real-time information about the energy usage and costs. The proposed hierarchical architecture includes data centers, communication layer, management systems, and energy suppliers, which can cooperate with each other through a set of interfaces to avoid power outage and reduce energy consumption during peak usage periods.

In summary, the smart grid can provide flexibility and intelligence in electric power utility services. Reliable communication is a key to achieve these objectives. Both wired and wireless communications have been investigated and used in this context. However, issues related to reliable and effective communications need to be further addressed.

### 3. Demand Response Applications

Demand-side management can be a major beneficiary of the smart grid systems. The key goal of demand-side management is to allow the utility company to manage the userside electrical loads. A very popular component of demand-side management is developing incentives for the smart grid customer, such as residential home users, to modify their temporal use of electricity, for reducing the peak-to-average load on the grid. Incentives can come in the form of lower pricing or coupons, among others. Note that demand-side management is strongly connected to demand-response models, as the two concepts can generally be grouped under programs that seek to shape the demand and supply for a more efficient energy consumption in the smart grid.

Demand-side management techniques are expected to be a major step in the realization of the smart grid systems. Indeed, enabling the interconnection of consumers, electric cars, microgrids, and utility companies can only be made possible with efficient demand-side management. Due to the complex interactions between customers and the power company, as well as the need for pricing schemes, demand-side management has often been studied using tools from game theory [15], optimization, and microeconomics [16]. There have been several contributions on demand-side management in the literature and these can be grouped into those focused restrictively on the economic aspects [17–25] and those that factor in grid-related issues such as frequency or voltage regulation [26–29].
In [19], a noncooperative game for load shifting is proposed. In this setting, each customer attempts to find the best way to schedule its appliances depending on the pricing information provided by the power company. It is shown that, under such a setting, whenever customers have enough “shiftable” appliances, significant energy savings can be reaped. Using particle swarm optimization, the work in [20] addresses the energy scheduling problem from a new angle, by incorporating the presence of distributed energy resources. Insights on the complexity of the optimization problem are provided, to allow the customers to better determine the trade-off between complexity, cost, and the need to schedule their energy resources. In [28], the focus has been on the potential of demand response within a DC microgrid network. The proposed approach allows controlling the parameters of the power electronic loads, so as to ensure efficient grid operation. Using both optimization and pricing mechanisms, the merits of having demand response within a microgrid network have been shown. The idea of combining demand response with grid constraints is also studied in [27] for AC networks. Here, the load management problem while factoring in power flow constraints has been studied.

The use of storage units as a key element in demand-side management is studied in [23]. Here, it has been shown that the use of storage can reduce peak demand, if the customers act strategically. The results are then corroborated via an empirical study on the UK market. The pricing problem as it relates to demand-side management is studied in [24] using a combination of game theory and auctions. There, the focus has been on studying the possibility of selling energy stored at the customer premises to the grid and/or other customers. Using the developed two-level game, it is shown in [30] that (a) a Nash equilibrium exists, even if pricing introduces a discontinuity and (b) the overall allocation of energy at the equilibrium outperforms conventional greedy solutions. The study of user behavior in demand-side management is discussed in [18]. In this work, approaches are proposed, using any of which, a power company can predict outages or costs on the customers and, subsequently, offer demand-side management contract. Several insights on the feasibility of demand response are provided. Shaping the demand is discussed in [17], using oligopolistic markets. The derived models provide a blueprint for integrating demand-side management and appliance-level scheduling. Other notable-related works include a study on the economics of load management in electric vehicle networks [22], incorporating reserve shortage prices [25], and quantifying the effect of user participation [21], among others.

In a nutshell, demand-response schemes that enable efficient management of the power supply and demand are expected to be an integral part of the smart grid. One of the key challenges of designing demand-side management models includes the need for modeling customer behavior. Other challenges that must be overcome before deploying demand-response model include modeling customer participation, developing decision-theoretic tools, optimizing pricing, incorporating time-varying dynamics (e.g., fluctuating demand), and accounting for power grid constraints. All of these issues motivate the need for decision-theoretic tools such as game theory, optimization, or stochastic control to properly model and analyze the various arising demand-response situations. It can be expected that demand response will be an important stepping stone towards practical deployments of the smart grid.

4. Microgrid and Integration of Energy Sources

Recently, distributed generation (DG) has become extremely important due to the growing global interest in reliable and sustainable electric power supply, to incorporate more renewable and alternative energy sources and to reduce the stress and loss in existing transmission system [31]. In DG, different energy resources can be incorporated to form an energy system that can meet the demand of local users. The emphasis in distributed generation is increasing as it can also conveniently support electrical energy needs in remote and rural areas [32], where no main utility power grid exists or is unreliable. A microgrid, in this context, refers to a controlled system of a cluster of loads and distributed microenergy sources that can provide electrical power to its neighboring areas [9, 32]. It can effectively coordinate different types of distributed energy resources through local power managements.

The U.S. Department of Energy has defined a microgrid as “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid (and can) connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.” A microgrid is considered to be the building blocks of future smart grids [33] with participation of multiple small-scale renewable energy sources. A conceptual illustration of a microgrid within the context of a smart grid is shown in Figure 2.

Electric power can be generated at a distribution level in a microgrid. It usually includes a variety of small power generating sources, as well as energy storage systems such as batteries, flywheels, and supercapacitors [31, 34]. The power generating sources may include renewable sources such as solar panels and wind turbines, which are typically located close to the consumer sites [31]. A microgrid can be coupled with the utility power grid through a single connection, known as point of common coupling (PCC). The electrical energy can flow in either direction through this coupling, based on the available energy generated within the microgrid and the demands of the consumers within the microgrid. A microgrid, when disconnected from the main grid, is known as an “islanded microgrid.” In an islanded microgrid operation, DGs continue to power the users of the microgrid without requiring to obtain electric power from the utility grid [33, 35]. The connect and disconnect processes in a microgrid are specified by the PCC.

The capability of islanding a microgrid offers several advantages and conveniences. For example, a microgrid can provide self-healing in the event of an outage or a power quality problem in the utility grid by switching to islanded
mode and then can switch back once the disturbance is over [31, 33]. Furthermore, a microgrid user can take power from the utility grid at a time when not enough power is generated within the microgrid, or when the price of the utility grid power is cheaper. On the other hand, any excess power generated by energy sources in the microgrid can also be fed into the utility grid.

Traditional power system is not designed to incorporate power generation and storage at the distribution level. It is also not designed to allow the distributed energy sources to supply the power to the customers directly [34]. Interconnecting and integrating distributed energy sources to power grid, therefore, is a challenging task. Due to the involvement of significant and critical technical issues associated with such integration, it has attracted significant research attention [34]. For example, the operating characteristics of different distributed energy sources can be different [36], which needs to be addressed appropriately. In this regard, researchers have investigated [34] the stability of a power system with the integration of fuel cells and microturbines [37–39], large scale wind turbines [40, 41] and solar panels [42, 43]. The weather condition and time of the day can add further complexity for wind and solar power generators [34]. Therefore, it is extremely important to have a clearly defined standard and procedure for integrating different distributed energy sources into microgrids [36].

Power electronic can play an important role in microgrid integration. Distributed energy sources can interface with a microgrid through rotating machines or through electronically coupled units that utilize power electronic converters to provide the coupling media with the host system [44]. The interfaces between the microgrids and prime movers can be based on power electronic converters acting as voltage sources (or voltage-source inverters in AC microgrids) [45]. These power electronic converters are connected parallel through a microgrid. In order to avoid circulating currents among the converters without the use of any critical communication between them, droop control method is generally used; however, it suffers from load-dependent frequency and amplitude deviations, which can be resolved by installing a secondary controller, implemented in the microgrid central control [45].

The output voltage of distributed energy resources can be DC or AC with a variable frequency. Unregulated output voltage and intermittent nature of renewable energy sources require the use of power converters for integration of the energy sources to the utility grid [46]. Voltage sourced converters (VSC), coupled with isolating transformers, are commonly used for this [46]. Designing grid connected VSC systems may face issues, leading to a distorted line voltage. In [46], modeling and control system design for a three-phase VSC system is investigated. After presenting a model for control system design, simulation, and stability analysis, a control strategy that regulates active/reactive power generation and mitigates the effect of grid voltage distortion on line currents is proposed in [46].

A microgrid is desirable to have a simplified operation capability so that an entity, for example, energy storage system, or a controllable load can be added without requiring a system level reconfiguration. Proper control, or an energy management system, is imperative to ensure system stability, reliability, and efficiency while integrating multiple energy sources, storages, and controllable loads. The measurements taken from different components of microgrids need to be communicated to the control system that can then decide on optimal operation for each component, based on the available information of the current states and the operating conditions [36].

Figure 2: An conceptual illustration of a microgrid.
The control paradigm can be centralized, distributed, or hybrid [36,44]. In a centralized approach, microgrid central controller receives all measurements from a microgrid. It then makes decisions based on some prespecified constraints and objectives, often by prioritizing energy utilization among the distributed energy sources in the microgrid, depending on the market prices and security constraints [36,44]. The various objectives can be conflicting and the multiobjective problems may not have a unique solution but instead may lead to some compromises and trade-offs among the objectives [36]. Microgrid central controller can issue control set points to distributed energy sources and controllable loads, which can be communicated over wired or wireless channels [44].

In the distributed control paradigm, the measurement signals from energy sources are communicated to the respective local controller. The local controllers, which communicate among themselves to form a larger intelligent entity, and make decisions on the best possible set of operations to improve the overall performance of the microgrid [36,44]. This approach provides autonomy for distributed energy sources and loads within a microgrid. A distributed approach facilitates integration of the energy sources. The load on each controller is reduced. It also eliminates the problem of single-point failure [36]. However, it also greatly increases the communication complexity of the system [36]. This problem can be handled by intelligent algorithms, for example, fuzzy logic, neural networks, and genetic algorithms, as discussed in [36]. For power management, system integration and restoration, multiagent approaches have also been used to achieve the objective effectively [36]. Finally, the hybrid control paradigm combines the above two schemes, where centralized control is applied in each group. On the other hand, distributed control approach is used among the groups [36].

In summary, microgrids can increase the reliability of power supply locally through active control of internal loads and generations. It can incorporate renewable energy sources, which helps to reduce environmental pollution [33]. Furthermore, it can limit feeder losses, improve voltage quality, and provide uninterrupted power supply [32]. However, integration rules must be made consistent [8] and technical issues must be resolved before these benefits can be fully reaped.

5. Security in Smart Grid

A smart grid is a large-scale system that extends from a power generation facility to each and every power consuming device such as home appliance, computer, and phone. This large-scale nature has increased the possibilities of remote operation of power management and distribution system. With energy being a premium resource, ensuring security against theft, abuse, and malicious activities in a smart grid is of prime concern.

The challenges of ensuring cybersecurity in a smart grid are diverse in nature due to the diversity of the components and the contexts where smart grids are deployed. Deploying a smart grid without strong and diligent security measures can allow advanced cyberattacks to remain undetected, which can eventually compromise the entire system [47]. Inadequate security measures can also compromise the stability of the grid by exposing it to, for example, utility fraud, loss of confidential user information and energy-consumption data [48].

The cyber security objectives can be classified into the following three categories [47,49].

(i) **Integrity.** Protecting against the unauthorized modification or destruction of information. Unauthorized information access opens the door for mishandling of information, leading to mismanagement or misuse of power.

(ii) **Confidentiality.** Protecting privacy and proprietary information by authorized restrictions on information access and disclosure.

(iii) **Availability.** Ensuring timely and reliable access to information and services. Availability can be compromised by disruption of access to information which undermines the power delivery.

Availability and integrity are the most important security objectives in the smart grid from the perspective of system reliability. However, due to the systems interactions with customers, the importance of confidentiality is also growing in this two-way data communication system that interconnects the whole system including meters, collectors, communications network, and utility data centers [47].

As mentioned earlier, smart grid has introduced new concepts in energy sector such as real-time pricing, load shedding, demand management, and integration of distributed, renewable power sources. It is based on numerous control systems, which can be targeted by the attacker. Furthermore, smart grid has created many more access points and with commands emanating from interfaces in homes and businesses in HAN [47]; any of these access points can be manipulated by the attackers to penetrate a network, gain access to control software, and alter load conditions to destabilize the grid in unpredictable ways [47]. It is important to note that attack at any point can affect the entire smart grid as it is mostly based on mesh network, and any malignant attack can propagate to the entire grid, as all components in a smart grid can communicate with each other. One particular point of concern in this regard is from a customer meter to the data collector, which can use wireless communication. This can provide an opportunity to the attacker, if security mechanism is not adequate [47].

Smart grid security mechanism should be enforced at several layers including physical and logical layers [47]. Physically, smart grid systems and component must be secured from harm, tampering, theft, vandalism, and sabotage. Examples of physical layer security include installation of fence, video surveillance, and alarm system [47]. Security in the logical layer deals with protecting the digital data. In [47], a detailed discussion on logical layer security mechanisms has been presented; a few of these are highlighted below.
(a) **Encryption.** Data encryption in smart grid, from meter to utility center, is a useful tool to prevent snooping, hence preserving the confidentiality of data. Strong but efficient algorithms can be used; however, all smart grid devices, for example, meters, collectors, processors, and routers, must be enabled with encryption processing capabilities [47].

(b) **Authentication.** It is the process of determining that a user or entity is, indeed, the same as been claimed. Smart grid applications must have strong authentication capabilities, to detect and reject unauthorized connections between its components, for example, meter and the utility interfaces [47].

(c) **Application Security Controls.** Smart meter applications should be designed and coded appropriately so that cybercriminals cannot access a meter to mount buffer overflow attacks or to embed a malware. Data validation is an example of techniques that can be used [47].

(d) **Security Patches.** It can protect an application from known threats; therefore, codes should be kept up to date with latest security patches [47].

(e) **Malware Removal.** Use of antivirus and antisympware software throughout the smart grid applications can help to detect and to remove malwares from the system [47].

Ensuring cyber security in smart grid needs continuous monitoring so that any possible attack can be detected in time and appropriate actions can be taken quickly. Also, monitoring various smart grid parameters can help identifying any suspicious or abnormal activity. Furthermore, having a rapid restoration plan is also important [47].

Recently, some research has been done to address security issues in smart grid. In the following, a few approaches proposed to handle security issues in the smart grid are outlined.

(i) **Public Key Infrastructure.** A public key infrastructure (PKI) based solution is proposed in [50]. PKI is a mechanism that binds public keys with unique user identities by a certificate authority (CA). Users have to obtain certificate public keys of their counterparts from the CA before initiating secure and trustworthy communication with each other. The scope of a PKI also encompasses policies and procedures, specific to the security requirements of a domain, on a combination of hardware and software platform. Under the scheme proposed in [50], various participants in a smart grid require communicating through a PKI system. The security standards for such a smart grid are also presented in [50].

(ii) **Anonymization.** The usage (of energy) data needs to be sampled at a high frequency for real-time load balancing in a smart grid. This kind of data also exposes the most amount of sensitive information. An approach to protect this confidential information by anonymization is presented in [51]. The idea is that attributing the usage data is not required unless it is for billing purpose. Sampling for billing can be performed at a lower frequency without negatively affecting the performance of automatic load balancing mechanism. Sampling for demand sensing and load balancing can be carried out in an anonymous manner at a higher frequency.

(iii) **Privacy Preserving Smart Metering.** The information network in a smart grid frequently transports confidential information relating to customers, for example, identity, location, possession of electronic appliances and devices, and power usage profile. Due to the increasingly important role of privacy and proprietary information in a modern socioeconomic landscape, protecting the privacy of a user is of significant importance. Several solution approaches have been proposed in this regard, one of them is a privacy preserving smart metering scheme [52]. The steps of this scheme are as follows.

   (i) The meter transmits certified readings of measurements to the user through a secured channel.

   (ii) The user calculates the final bill by combining meter readings with a certified tariff policy.

   (iii) The bill is transmitted to the provider alongside a zero-knowledge proof that validates the calculation.

   No other data is transmitted from user to the service provider. By limiting the data exchange to only the billing information the user’s privacy is preserved. The proposed approach in [52] has the flexibility to incorporate different tariff schemes as well as certification techniques.

(iv) **Distributed Data Aggregation for Billing.** A distributed incremental data aggregation approach for billing is presented in [53]. A special entity, called the aggregator, acts as the root of the aggregation tree that covers all the meters in a given neighborhood. All smart meters in the given neighborhood follow the path dictated by the aggregation tree to forward their data towards the aggregator. The data en route is encrypted using homomorphic encryption. Homomorphic encryption represents a group of semantically secure encryption functions that allow certain algebraic operations on the plaintext to be performed directly on the ciphertext. Data is aggregated at each node of the tree before being forwarded to the upper level. The aggregator is responsible for maintaining communication with the service provider. Since the smart meters taking part in data aggregation and forwarding can see only a fragment of the final result, the user’s privacy is protected. It has been claimed in [53] that this approach is suitable for smart grids with repetitive routine data aggregation tasks.

(v) **Collaborative Usage of Resources.** The dynamic demand against somewhat constant energy supply in a smart grid can be met by collaborative usage of resources. This allows a decentralized, somewhat autonomous, local distribution. However, since several entities in a grid share the pool of energy, it is also possible for one or more malicious entities on the grid to selfishly demand more energy while depriving other users sharing the same pool. To counter this kind of malicious or selfish behavior, the concept of collaborative
customer and a collaborative resource usage scheme called the “voucher scheme” is introduced in [54]. By grouping two or more entities together to share energy, a level of decentralization can be achieved. In the scheme proposed in [54], the central authority supplies energy to the group, and the group distributes the energy among the members depending on their demands. This reduces the need to send sensitive information to the central point of control. Within the group, a power user in need of extra power issues a voucher, a certificate which is immune to various security attacks, to another power user who is willing to transfer the right to use power to the former user. Thus both parties gain monetary benefit.

To summarize, the smart grid has opened up many opportunities, also many security risks. Protecting the energy generators must be given highest priority, in addition to protecting the privacy of the consumers. Power houses can be attractive terrorist targets, as much as defense installations. Therefore, in order to achieve the benefits of a smart grid, it is imperative to develop a network solution that is highly reliable and secure.

6. Summary

In this paper, several features of the smart grid have been discussed that include communications, demand response, security, microgrid, and integration of new grid elements such as renewable energy sources. The available literature indicates that reaping the full benefits of the smart grid is contingent upon meeting a number of challenges at different grid levels, from communication infrastructure to energy management and security. The smart grid is a vast, interconnected system, with many new and emerging components and applications, which requires a thorough investigation on the interoperability issues as well. Clearly, numerous technical challenges and issues associated with effective and secure communication and information processing must be resolved before realizing the vision of a smarter power grid.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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