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Smart Grid and Electric Vehicle: Overview and Case Study

Umair Shahzad
Department of Electrical and Computer Engineering,
University of Nebraska-Lincoln,
Lincoln, NE, USA
umair.shahzad@huskers.unl.edu

***Abstract*–As the energy demand is continuously increasing, the smart grid technology is gaining importance. In recent years, smart grid has turned out to be an important topic that can strongly tackle the present issues and future challenges of energy. The vital elements of a typical smart grid are dependable supply of energy, unconventional generation, and controlling energy demand through smart meters. Moreover, communication is a momentous component of smart grid. This study aims to discuss the communication technologies, challenges, and prospects for smart grids. Electric vehicle is an integral part of smart grid. Therefore, a case study on IEEE 13-bus test system is demonstrated to signify the impact of electric vehicle on power system reliability. In the end, some possible future research directions are suggested.**

Keywords-Communication; electric vehicle; energy demand; reliability; smart grid; smart meter

I. INTRODUCTION

Smart grid can be defined as “a power grid which utilizes communication and information technology to collect data, and consequently acts on information about the behavior of consumers and suppliers in a robust manner” [1]. Gone are the days when traditional power system can be relied upon. In today’s systems, the decisions need to be made swiftly. For instance, in traditional systems, circuit breaker tripping time is in the range of milliseconds, at most. With the advent of smart grid, this time can be crunched, even to micro and nanoseconds. This is essential as it will lead to an increase in overall reliability and stability of the system. Moreover, the trend of renewable energy is increasing due to hazards of global warming and greenhouse gases. Smart grids can easily incorporate many renewable energy resources and help in producing clean energy. Therefore, the smart grid is the need of the hour and hence, it entails a lot of significance. Fig. 1 shows the interactions of various domains of smart grids. Fig. 2 elaborates the basic functions and attributes of a typical smart grid. Table I enlists basic differences between a traditional and smart grid [1-2].

The major components of a smart grid constitute of smart power meters, smart appliances, smart distribution, smart substations, smart generation, and universal access. These components are shown in Fig. 3.

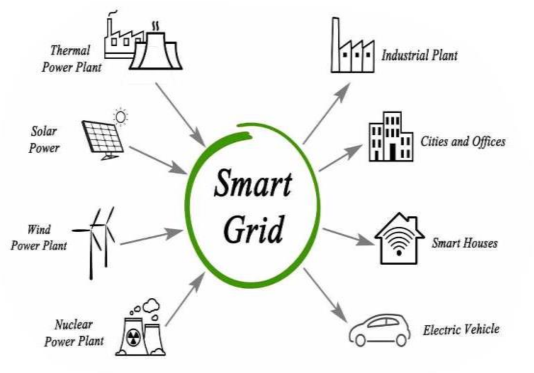

Fig. 1. Exchanges between diverse smart grid fields

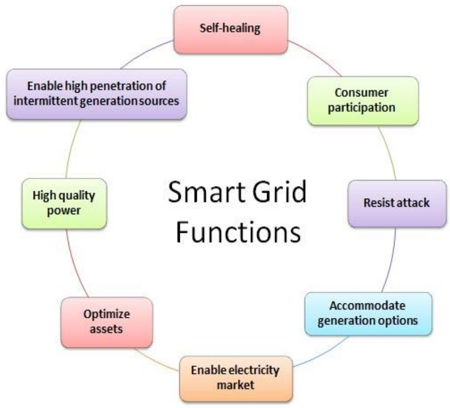

Fig. 2. Main functions of a smart grid

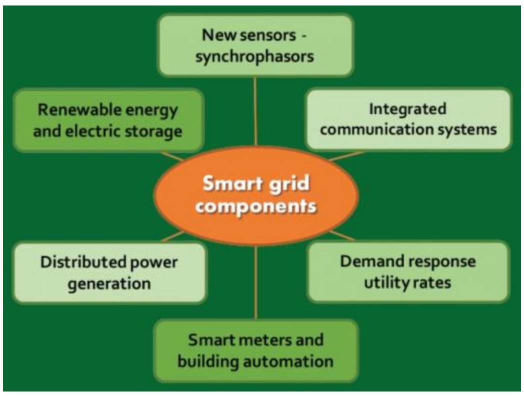

Fig. 3. Main parts of a typical smart grid

The rest of the paper is organized as follows. Sections II and III discuss various smart grid technologies and significance of wireless communication in smart grids, respectively. Sections IV and V discuss challenges, and prospects of smart grids, respectively. Section VI discusses brief interaction of smart grids with electric vehicles (EVs). Section VII demonstrates a case study to assess the impact of EVs on the power system reliability. Finally, Section VIII concludes the paper with suggested future research directions.

TABLE I. TRADITIONAL AND SMART GRIDS: A COMPARISON

Traditional grids	Smart grids
Mechanization	Digitization
One-way communication	Two-way communication
Central power generation	Distributed power generation
Radial configuration	Network configuration
No automatic monitoring	Automatic monitoring
Manual recovery	Automatic recovery
Finite control	Universal control
Inadequate pricing information	Comprehensive pricing information
Fewer user options	More user options

II. SMART GRID TECHNOLOGIES

There are three important technologies which are incorporated into a typical smart grid. They are discussed below [3-4].

A. Smart Transmission Grid

Smart transmission grid has gained a significant position in recent times. It is needed to distribute the electrical energy to the loads. With the rising popularity of DC power transmission, the probability of the transmission has been expanded to HVDC transmission at numerous voltage levels.

A great advantage of smart transmission grid is that it enhances power transmission quality and reliability in a cost-effective manner. This is because it can perform various functions such as reactive power compensation, control, and protection of sensitive equipments and power flow analysis in a flexible manner.

B. Information and Communication Technology

There are some disadvantages of traditional grid. Some of them include the absence of perceptibility, fatigued reaction time of mechanical switches, and absence of situational awareness. The technologically-advanced construction of smart grid augments the adaptability, and capacity of the communication network, and provides advanced monitoring and organization, using latest communication technologies and protocols. For instance, if there is a fault at any location of smart grid, the enhanced communication technology can be utilized to trip the associated circuit breakers within microseconds. In this manner, the sensitive equipment of the network will be saved from major failure.

C. Smart Metering Technology

Smart metering technology has been utilized to measure various patterns in energy communication proficiently. Existing electrical meters also employ this useful technology. It is employed to measure the energy consumed by the consumer and provide a great chunk of useful information to the utility companies, which the conventional energy meters cannot. It has various control and communication functions which enable it to do so. For instance, if a user is using power greater than the certain amount, the smart meter will ring an alarm to alert the user. Moreover, the user can have more control in utilizing energy during peak load hours.

III. WIRELESS COMMUNICATION FOR SMART GRID

There are two major wireless communication technologies employed in smart grid. They are called Local Area Network (LAN) and Home Area Network (HAN). They are discussed below.

A. LAN Technologies

These technologies are employed in LAN which utilizes unlicensed frequency bands to operate such as Bluetooth, Zigbee, Wi-Fi. Each of these technologies has their own implication and restriction as discussed below [5-8].

Bluetooth is a low-cost technology which is employed for the smart grid communication inside the individual LAN for investigating the energy utilization by any specific component. It can also aid in providing motion such as switching a power element in and out of the smart grid. The three main advantages of using this technology are: (1) it has low power consumption, (2) it can be used for voice and data transmission, and (3) it uses Frequency Hopping Spread Spectrum (FHSS) and hence, the data communication is highly secure. However, the bandwidth of bluetooth is lower compared to Wireless Fidelity (Wi-Fi).

Zigbee is a cost-effective technology used for communication in smart grid communication applications within the HAN. It has a greater coverage bandwidth than the Bluetooth connection. It is beneficial for examining the energy usage of various electrical parts in the home and aids in the routine operation of automatic metering and lightning. The two main advantages of using this technology are: (1) it does not have any central controller which allows the loads to be distributed evenly across the network, and (2) it is very simple to monitor and control home appliances remotely. However, this technology is not secure like Wi-Fi-based secured system, and hence, is vulnerable to attacks from unsanctioned personnel.

Wi-Fi is an acronym for Wireless Fidelity. This technology is used for broadband internet connection within the LAN. This technology is used for wirelessly managing various functions of a smart grid like monitoring of automatic protection and control devices in different local areas. The two chief advantages of using this technology are: (1) wireless networks allow multiple users to connect through the same network, and (2) installation is very rapid and simple. It does not require any technical knowledge of Wi-Fi system and its related protocols. However, data transfer rate rapidly decreases when many users simultaneously connect with the network.

Table II illustrates a basic comparison between Bluetooth, Zigbee, and Wi-Fi.

TABLE II. A COMPARISON BETWEEN BLUETOOTH, ZIGBEE, AND WI-FI

Standard	Bluetooth	Zigbee	Wi-Fi
IEEE spec.	802.15.1	802.15.4	802.11a/b/g
Frequency band	2.4 GHz	868/915 MHz; 2.4 GHz	2.4 GHz; 5 GHz
Maximum signal rate	1 MB/s	250 KB/s	54 MB/s
Nominal range	10 m	10-100 m	100m
Channel bandwidth	1 MHz	0.3/0.6 MHz; 2 MHz	22 MHz
Spreading	FHSS	DSSS	CCK, DSSS, OFDM
Data protection	16-bit CRC	16-bit CRC	32-bit CRC

B. HAN Technology

This technology is the best technology for communication between smart meter and residential loads. ZigBee is a suitable candidate for an economic communication medium for HAN. Smart meters have the competence for connection to the HAN. This will allow customers to be conscious of the expenses incurred by using various power equipments. Among home electrical appliances and smart meters, HANs allow the users to monitor their power consumption using home displays or a smart tablet. This is possible due to low-bandwidth communication capability of HAN within smart meters and household electrical components [1]. The two chief benefits of using this technology are: (1) it gives better accessibility for all the users, and (2) it provides improved security, as it is equipped with sophisticated security softwares, passwords etc. which protect it from unlicensed access. However, setting up of HAN is somewhat costly because it requires smart devices (smart washing machines, smartphones, etc.) to work in the network.

IV. CHALLENGES OF SMART GRIDS

The smart grid system is a complicated network that faces a wide array of challenges. Smart equipment such as Intelligent Electronic Devices (IEDs) will require robust amounts of embedded computing equipment that must be replaced every 5–10 years. Along with the vigorous computing systems, the communications technologies being implemented in smart grid systems are at different levels of development and implementation. This further produces issues as to what devices will be best suited for the long-term future of the smart grid system. Management of all the data that will be communicated is another challenging aspect of future smart grids. The management of data is an extremely time-consuming process that is made further complicated through the immense scale of a smart grid system. Another issue with adoption of smart grid technology seems to be an absence of mindfulness by people associated with designing smart grid systems and an absence of consistent regulatory guidelines. The present electrical network consists of numerous distributed nodes which are strongly coupled. Since all network components have gradually increased over years, finding out where intelligence needs to be placed is quite complicated. Another main issue is to integrate substitutable components from various distinct providers. There is a dire requirement for interoperability standards that will permit utilities to purchase components from any retailer knowing that they will co-exist with one another, and with present equipment, at all possible levels [9].

V. FUTURE OF SMART GRIDS

In traditional power systems, load demand was fixed and predictable. As energy costs have started to vary, in addition to environmental concerns, customers' intertest in having more "control" in changing their energy usage has increased. This interest will further boost the significance of replacing traditional grids with smart grids. Another important aspect is that of introduction of EV as a "new" load in the power system. With its popularity increasing gradually, power utilities are eyeing the advent of a huge new market. With the evolution into smart grid, the grid will be more observable and controllable. This means the system operators will have a comprehensive knowledge about the state of the power system. Moreover, this will enable them to have a greater command on control and sensors signals associated with Supervisory Control and Data Acquisition (SCADA) systems. In view of the above-mentioned points, the timing is apt to consider an update to a modern grid which is resilient and robust in every way as compared to the conventional grid. Some countries have already started moving towards this goal and are rewarding the customers who make use of smart metering. Overall, this will assure a more sustainable future for the mankind [10]. Fig. 4. pictorially represents various future needs of smart grid.

Fig. 4. Future needs of smart grids

VI. ELECTRIC VEHICLE AND SMART GRID

As mentioned before, smart grid constitutes of various advanced technologies, control and metering services. These are very useful for EVs as dynamic loads and potential distributed energy sources [11]. Fig. 5 illustrates a schematic for a typical EV. Various researches have been performed to evaluate the smart grid infrastructure for development the EVs penetration in the power grid. Standards and specifications for interoperability and seamless incorporation of the EVs into the power system have also been published [12-13].

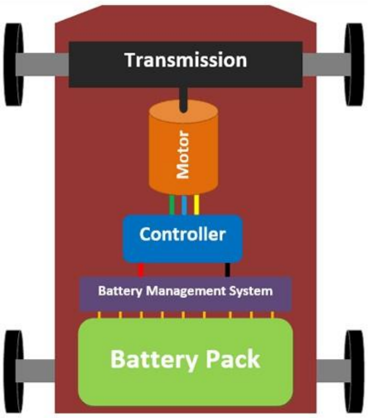

Fig. 5. Schematic of a typical EV

The objective of energy management system in a typical smart grid can be achieved through monitoring and recording the energy usage in real-time. The role of smart meters is very vital in this regard. It can be very helpful to monitor energy consumed or supplied in the network [14]. Fig. 6 shows a typical interaction framework for EVs in a smart grid environment [12]. The smart meters communicate using various smart grid technologies, such as, Worldwide Interoperability for Microwave Access (WiMAX), LAN, or HAN. The EV utility can acquire the energy information through the meter data management system (MDMS). By means of the consumer web portal; the human machine interface can be comprehended between the EV management system (EVMS), MDMS, utility service provider and the energy market [12].

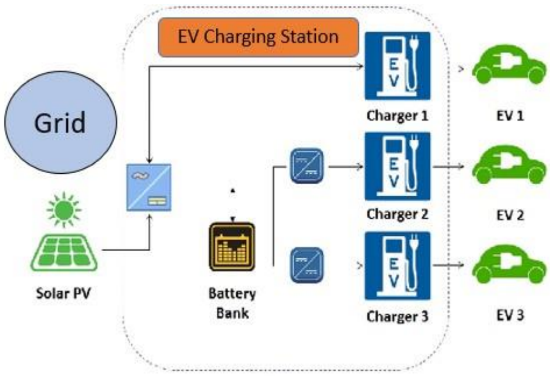

Fig. 6. Interaction of EVs in smart grid environment

Relying on the charging mode, the EV charging station is generally powered from either the main grid or from the solar PV system. The grid mains AC is rectified using a diode bridge rectifier and consequently, the filtered output is given to a DC-DC converter. The output of the converter is maintained at the EV battery voltage value and is used to charge the EV.

VII. IMPACT OF ELECTRIC VEHICLE ON SMART GRID RELIABILITY

As mentioned before, EV is a significant component of smart grid. Thus, it is important to observe its impact on the power system. This section briefly presents a case study to discuss the impact of EV charging stations on the reliability of IEEE 13-bus test system (one-line diagram is shown in Fig. 7). Although, some work has been done in this aspect [15-19], but there is a lack of research on quantifying the impact of EV charging stations on power system reliability.

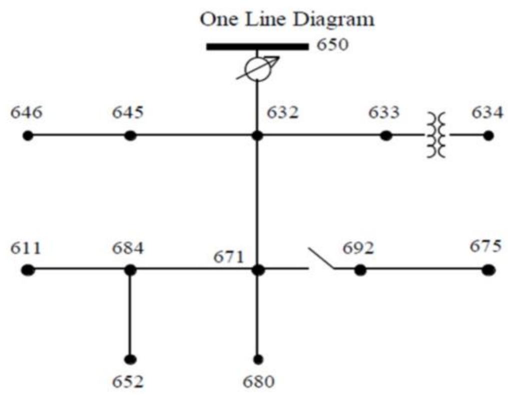

Fig. 7. IEEE 13-bus system

Level 1 topology [21] was used in this paper. It consists of a non-isolated bidirectional two-quadrant charger as shown in Fig. 8. The topology (buck converter) is then solved for determining the capacitor size. The optimal value of capacitance size (C) comes out to be 200 μF. The solution procedure is out of scope of this paper. The reader can refer to [22] for the detailed solution. EV topologies generally include a DC bus, demarcated by the battery pack voltage, electric traction motors and other loads. The charging systems are categorized based on power and voltage levels: Level 1, Level 2, and Level 3. Higher charging rates mean shorter times for charging the battery. Tables III and IV enlists the various charging levels for some common EVs [20,21].

In this paper, various reliability indices such as Bus Reliability Index (BRI), System Average Interruption Frequency Index (SAIFI), and System Average Interruption Duration Index (SAIDI) are used to quantify the impact of EV on the IEEE 13-bus distribution network. The definitions of these indices can be found in [23]. In the first step, value of BRI for all buses (except slack bus 650) in the system is computed. For this purpose, outage data is taken from

[24]. DIgSILENT Power Factory commercial software was used to conduct simulations.

TABLE III. CHARGING FEATURES OF COMMON EVS (LEVELS 1-2)

Battery type	Level 1 Rating (kW)	Level 1 Charging time (hrs)	Level 2 Rating (kW)	Level 2 Charging time (hrs)
Toyota Prius	1.4	3	3.8	2.5
Nissan Leaf	1.8	12-16	3.3	6-8
Tesla Roadster	1.8	30+	9.6-16.8	4-12

TABLE IV. CHARGING FEATURES OF COMMON EVS (LEVEL 3)

Battery type	Level 3 Rating (kW)	Level 3 Charging time (hrs)
Toyota Prius	N/A	N/A
Nissan Leaf	50+	0.25-0.5
Tesla Roadster	N/A	N/A

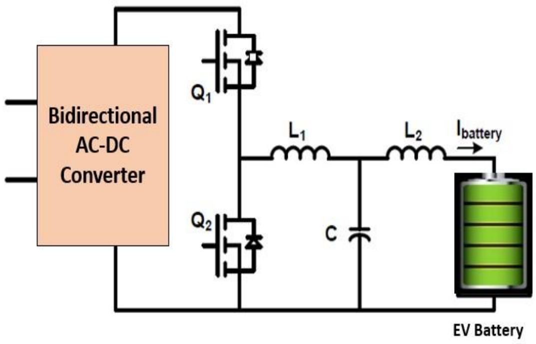

Fig. 8. Charging station topology (non-isolated)

The values of BRI obtained for various network buses are listed in Table V.

A higher value of BRI implies higher vulnerability of that specific bus. Based on the values of BRI obtained, strong and weak buses of the system can easily be found out. The greater the BRI value for a bus, the least is its reliability. As evident from Table V, Bus 680 is the most reliable and Bus 632 is the least reliable. Thus, EV charging station is placed at these buses, one at a time. These case scenarios are outlined in Table VI.

The results for these cases are shown in Table VII. Note that base case means that no charging station was connected to the network. As evident from Table VII, both system indices deteriorate after addition of charging stations. Therefore, placing fast charging stations at the weakest system bus is very harmful to system reliability. However, slow charging stations can be placed at the weaker buses for reliability enhancement. Thus, placement of EV charging stations at both extremes of buses degrades the SAIFI and SAIDI values. In future, more such studies are required on real test systems [25].

The research on smart grids is just the beginning. Further research is required to completely understand their potential and possible impact on power system. Various research works suggest including the smart grid analysis in the power system planning and operational procedures, particularly with the increasing renewable generation penetration, involving risk assessment [26-37].

TABLE V. VALUES OF BUS RELIABILITY INDEX (BRI) FOR IEEE 13-BUS TEST SYSTEM

Bus No.	BRI
646	0.268
645	0.443
632	0.725
633	0.386
634	0.173
611	0.484
684	0.689
671	0.075
692	0.457
675	0.094
652	0.662
680	0.031

TABLE VI. TWO CASES CONSIDERED FOR RELIABILITY ANALYSIS

Case No.	Description	Load Increase (MW)	No. of charging points
1	Charging station at Bus 680	2	50
2	Charging station at Bus 632	2	50

TABLE VII. IMPACT OF CHARGING STATIONS OF EV ON INDICES OF RELIABILITY

Case No.	SAIFI (interruption/year)	SAIDI (hour/year)
Base case	0.053	0.406
1	0.154	0.446
2	0.168	0.551

VIII. CONCLUSION AND FUTURE WORK

The paper discussed the significance of smart grids. Associated technologies, along with challenges and prospects were also a part of this research. A case study on the IEEE 13-bus test system was conducted to bring into light the significance of using EV charging stations. There are numerous means of communication possible for smart grid applications; however, determining the optimum one is one of the most challenging steps. With the advent of latest technologies in power systems such as Phasor Measurement Units (PMUs) and IEDs, the future of smart grids is bright. Some possible research directions, on smart grids, in the future could be cloud-based control and management, power flow optimization enhancement, and power system protection. Determining the optimal size and location of EVs in smart grid, considering various dynamics involved, is also a potential research problem.

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