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A study on Vulnerabilities of Integrating Variable Renewable Energy Resources in Smart Grid Network

Kiran

B.Tech (EE), PGDESD, M.Tech (EE), PGDET
Research Scholar
Uttarakhand, India

Abstract

In the 2015, the adoption of Paris Agreement proved to be a milestone in International climate politics and brought years of attempted negotiations to a conclusion, as countries agreed on setting targets for reducing greenhouse gas emissions, to combat climate change. The use of renewable energy sources is a major strategy for decarbonizing the global economy. In Power Generation, Renewable energy sources particularly photovoltaic and wind are considered important as the potentials of hydro, biomass or geothermal energy are limited in many countries. Power Generation using renewable energy resources is need of the hour but at the same time, maintaining the power system stability posses' challenges. The potential temporal mismatch of supply and demand raises question: how to deal with time varying renewable energy resources. With the recent advancement in monitoring, sensing, control and communication, plus the increasing penetration of renewable and distributed energy resources, the electricity grid is evolving toward an intelligent grid; smart grid is envisioned to achieve self healing, resilience, sustainability and efficiency. One of the major goals of the future Smart grid is 100% integration of Renewable Energy Resources (RERs). However, the disparate, intermittent, and geographically distributed nature of RERs complicates the integration of RERs into the Smart Grid and poses several challenges that need to be addressed in order to become effective. These challenges include the proper planning of the integration of renewable energy resources into the Smart Grid, Scalability issues, Regulatory issues, the standardization of the universal protocols, and standards for the seamless operation of the smart grid. This paper comprehensively examines the challenges to integrate variable renewable energy resources to the Power system- smart grid network.

Keywords- Smart Grid, Renewable Energy, Power Sector, Smart Grid Development, Smart grid Challenges

I. SMART GRID RENWABLE ENERGY SYSTEM

The increased awareness of the environmental impact and the carbon footprint of fossil energy sources in electric power production, has given an impetus to the growth and adoption of renewable energy as an alternative energy resource [50]. The electricity grid to accommodate higher percentage of renewable energy would need large quantities of conventional back up power and huge energy storage. These would be necessary to compensate for natural variations such as the amount of power generated depending on the time of day, season and other factors such as the amount of sunlight or wind at any given time [31] hence it is the demand of energy services that lead to energy planning where Technology acts as a link between the energy demand and energy supply. Due to the continuous proceeding of power-marketing people hope that the future state grid will be more renewable, robust, efficient, distributed and reconfigurable. Ensuring to meet these demands, smart grid integrates modern advanced sensor technology, measurement technology, communication technology, information technology, computing technology, and control technology into it, where the information and electricity flow will be bi-directionally [54]. Thus enabling the smart grid to incorporate features that enable active participation by customers, system that can accommodate generation and storage options, Supports new products, services, and markets, maintains power quality for the digital economy and Optimizes asset utilization so to operate efficiently. Thereby developing a system, that anticipates, responds to disturbances and Operate resiliently against attacks and natural disasters [29].One of the unique smart grid features is the incorporation of renewable energy resources (RER). The RER not only facilitates the injection of surplus energy from small consumers back into the grid, but also help in reducing Carbon dioxide emissions [34]. [18] has discussed the following significant changes attributed to the use of Smart grid systems-

Environment	Without Smart Grid System	With Smart Grid System
Data	Offline, Scarce data, One- way stream	Online, Abundant data, Two- way interchange
Power Restored	Artificial	Self- healing
Business Models	Producers and consumers Static business models	Prosumers Dynamic business models
Flow Control	Limited	Universal
Energy	Focus on fossil-based, non-renewable energies Centralized energy production	Focus on renewable energies Distributed energy production
Topology	Radial	Reticular

Environment	Without Smart Grid System	With Smart Grid System
Information and communication technologies	Weak preventive mechanisms Little use of information and communication technologies, Infrastructure with scarce intelligence	Strong preventive mechanisms Widespread use of information and communication technologies Information inference and decision making features
Agents	Reduced amount of participating agents	Potentially huge amount of participating agents

There are several ongoing global efforts that are put across the world for developing Smart Grid. India is adopting Smart grid Initiatives [11], Smart Grid Vision and Roadmap for India, National Smart Grid Mission (NSGM), and India Smart Grid Forum (ISGF) carrying out pilot projects. The Power Industry is embracing higher versions of technologies like smart grids to meet the obligations of 21st century. Now with support from all stakeholders of power sector, the smart grid success is possible but need to overcome few challenges [35]. Like any other technology smart grid faces certain technical, social and economic barriers [17].

The Technical challenge to attain a balanced smart grid network comprises of Integration of several devices with the grid network. It addresses attainment of distributed communication strategies with optimized latency and bandwidth, advanced control systems, reliable fault tolerance management techniques, efficient massive data processing methods and incorporating energy storage devices. Inadequate grid infrastructure in several power pockets, cyber security issues for utilities also poses a technical challenge [36]. With rise of new upgrading energy market brings economic challenge as it requires to develop new business models that help decide active demand response strategies which includes reducing peaks of consumption in power system, changing and shifting the consumption patterns. The regulatory challenges covers issues related to the establishment of standards at different levels of the smart grid network that will specify the basis for interoperability required to make the developed smart grids feasible [27].

In order to evolve towards a smarter grid, major research and development efforts are being concentrated in areas like **Wide-area monitoring and control systems** (WAMC) [6] which is responsible for preventing and mitigating the possible disturbances that might strike the grid. For this WAMC system performs advanced operations that intendeds to identify the presence of instabilities. The main function of a WAMC system is data acquisition, data delivery, and data processing [49]. An essential aspect of the smart grid is its response to real-time information exchange based on communication infrastructure that supports the integration of distributed and heterogeneous devices for this the second area of research is **Information and communication technology integration** [13].

The third, **Integration of distributed renewable generation systems** as the distributed generation consists of integrating many small power generation sources especially when sources of generation come from renewable sources, additional challenges arise to manage the unpredictability and controllability issues [50]. The research area for **Transmission enhancement applications** for Smart Grid network addresses research solution to find ways to increase the transmission capacity by resorting to different applications such as Flexible AC transmission systems, high-voltage DC, high temperature superconductors or dynamic line rating [42].

Another area of study is **Distribution grid management** of Smart grid that intends to perform tasks such as load balancing, optimization, fault throughout the different components of the distribution system [14]. One of the main tenets of the smart grid is using variety of sustainable conception for power generation and consumption process. For this, it is a priority to minimize the emission of green-house gases and electric vehicles provides a solution to this concern hence one of the main tenets of the smart grid is **Electric vehicle charging infrastructure** that could be used for more sustainable conception of the power generation and consumption process in which electric vehicles can play as a storage unit in the smart grid [7]. Advanced metering infrastructure for a Smart grid encompasses advanced metering system that provides enhanced functionalities along with metering and counting which includes dynamic pricing, to help consumers reduce their bills by adjusting their consumption to those periods outside the peak demand times. The advanced metering system is composed of three components: the smart meter, the communication utility, and the meter data management application [20]. It should be noted that there is a constant need for maintaining the system balance, in order to do that the advanced metering system is constantly researching advances to overcome interoperability problems.

The smart grid development for the **Customer-side systems** encompass applications that facilitates to make more efficient use of electricity as well as a cost reduction for the customer it covers issues like Energy management systems, storage devices, smart appliances and small generation systems [13]. While economic, environmental and energy security concerns have been the influencers for promotion and development of renewable energy sources, these sources are characterized by inherent issues like variability, intermittency and fast ramping etc. Flexible and strong smart grids play a crucial role in the integration of variable renewable energy (RE). As high levels of variable RE penetration become increasingly common across power systems, attention to grid operations and planning becomes more important. This section has summarized the most relevant aspects that are encompassed under the umbrella of the smart grid. The next section focuses on potential challenges in integrating renewable energy with the smart grid.

II. POWER QUALITY CHALLENGES IN RENEWABLE ENERGY SMART GRID INTEGRATION

Power quality is used to describe how closely the electrical power delivered to customers corresponding to the appropriate standard which operates end user's equipment correctly. Power quality is a measure of ideal power supply. Different organizations like the Institute of Electrical Engineers (IEEE) dictionary, the definition in the International Electro technical Commission (IEC) standard IEC 61000-4-30 have given various definitions of power quality [11] which could be generalized as the possibility of measuring and quantifying the performances of the power system and not related to the performance of equipment. [28] Discussed Power Quality Issue as any power problem manifested in voltage, current and/or frequency deviations that results in the failure and/or mal-operation of end users equipment whereas in [5] the power quality issue is defined as any power problem manifested in voltage, current or frequency deviations that results in failure or malfunction of customer equipment. Renewable energy offers alternative sources of energy which is in general pollution free, has less maintenance cost, low operational cost, environmental friendly, helps in reduction of greenhouse gas emission etc [25]. Renewable energy penetration not only affects the local market price but also helps in reducing the electricity price of adjacent interconnected systems. Variable renewable energy resources help increasing the consistency of the system by Low percentage but difficulty arises due to the high penetration of renewable generation into the smart grid. Several renewable energy sources are used to generate electrical power, such as wind energy, photovoltaic energy [44], wave energy, tidal energy, thermal energy, bio-mass energy for this government, utilities and research communities are working together to develop an intelligent power system that has potential to better the integration between the varying renewable energy resources with the smart grid [19]. Any device to be connected to the smart grid has to fulfill standardized power quality requirements. To ensure adequate Power Quality in the Smart grid, it is prime concern to mitigate following problems:

1. Voltage Fluctuations- It is a general observation that Wind and solar PV power generation both experience intermittency which is caused due to a combination of non controllable variability and partial unpredictability features of wind and solar resources [53]. As a wind turbine needs wind to generate electricity, and a solar PV system requires sunlight to operate but the wind speed and available of sunlight vary due to this the output of wind and solar power generation also varies. This non controllable variability could result in voltage and frequency fluctuations on the transmission system. This fluctuation in power output needs additional energy to balance supply and demand of the power grid on an instantaneous time basis which requires constant monitoring of frequency regulation and voltage support [52]

2. Voltage Sags and Swells- The functionality of Smart grid depends on its ability to coordinate between devices, customers, distribute generators and the smart grid operator. Voltage Sag occurs when the magnitude of RMS voltage decreases between 10 and 90 percent of the nominal RMS voltage for duration of 0.5 cycles to 1 minute. This can happen due to faults in the transmission/ distribution network. It can also occur due to faults in consumer installation, connection of heavy loads and startup of large motors [32]. The voltage swell is momentary or sudden increase of the RMS voltage, at power frequency outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds. It can be due to start/stop of heavy loads or ill-dimensioned power sources [37].

3. Harmonic Distortion- Integration of large-scale renewable energy sources introduces current and voltage harmonics due to power electronics devices as well as inverter connected into the Renewable energy sources. The Inverters connected with renewable energy sources, nonlinear customer loads and power electronics devices introduce harmonics in the distribution network that causes overheating of transformers, tripping of circuit breaker which reduces the life of connected equipments. Therefore, harmonics is one of the most dominant attributes that need to be kept in a minimum level to ensure Power quality of the network balanced. Harmonics increase line losses and cause excessive heating of equipment which decreases their lifetime [3]. The standards are IEEE 519-1992, IEC 61000-4-30 and EN50160. IEEE 519-1992 deals with the practices of and requirements for harmonic control in electrical power systems. It specifies the limits of harmonic voltage and current at the point of common connection between end user and distribution utilities [5].

4. Reactive Power Compensation- Power electronic converter (PEC)-interfaced renewable energy generators (REGs) are increasingly being integrated to the smart power grid. With the high renewable power penetration levels, one of the key power system parameter i.e. the reactive power gets affected giving rise to steady-state voltage and dynamic/transient stability issues. Therefore, it is imperative to maintain and manage adequate reactive power reserve to ensure a stable and reliable smart power grid. Along with REGs, conventional reactive power support devices (e.g., capacitor banks) and PEC-interfaced reactive power support devices (e.g., static synchronous compensators) play an indispensable role in the reactive power management of renewable rich power grids. Reactive power coordination between support devices and their optimal capacity are vital for an efficient and stable management of the power grid [29].

5. Power Grid Disturbances- Another power quality issue that affects renewable energy integration is power grid disturbances. The power grid-code requirement for grid-connected renewable power plants has evolved through a continuous evolution to ensure a reliable power system operation. The intermittent nature of the renewable resources and limited dispatch ability require grid operators to maintain additional spinning reserves. Accurate hourly and sub hourly solar generation forecasting is required to allow for unit commitment and spinning reserves , scheduling and dispatch. To ensure power quality, international standard such as IEEE 1159-2009 was developed to maintain the power quality at an acceptable benchmark. The standard provides the definition and characteristics of the power quality disturbances; and the recommendation on the design, installation, and maintenance of the sensitive equipments [47]. According to European grid-codes, a PV power plant must be able to ride through specific disturbances without disconnections [53]. In 2014, IEEE standard 1547a released a new definition for the voltage sag trip settings that would allow the equipment to ride through during voltage sag. This standard encircles a distributed generation not to trip if the duration of voltage sags is between default settings and the maximum setting and an agreement is set between the distributed resource owner and the local utility. An example is, Fault ride through capability, which helps in strengthening power system security due to the increase in the integration of wind power in recent times. It requires the generators to remain connected in the likelihood of a disturbance on the network as the newly installed wind turbines are designed to comply with grid connection requirements known as grid codes that demand wind turbines to ride through fault [47].

6. Flickers and Fluctuations: Flickers are the periodic voltage frequency variation that ranges between 0.5 and 25Hz which causes annoyance from the incandescent bulb. It is observed that flicker annoyance is severe at a frequency of 8.8Hz. The international electrochemical commission (IEC) standard 61000-4-15 describes the measurement of flicker given the instantaneous flicker level (IFl) and the probability short term (Pst) measure for a time span of 10 min, and the probability long term (Plt) measured for an average of 2 hours. For flicker free voltage the value is set at Pst = 0 whereas a Pst=1 indicates that the flicker pollution has reached the tolerable limit of an average person [45]. During normal operation, wind turbines produce a continuously variable output power as result of fluctuation in wind. The random nature of wind resources, in the wind farm generates fluctuating electric power if unregulated, the fluctuating electric power when injected to the power grid leads to the variation of wind farm terminal voltage due to system impedance. This power disturbance propagates into the power systems, which consists of fluctuations in the illumination level caused by voltage variations [33].

7. Synchronization: Synchronization of grid frequency, voltage, and phase is a promising research challenge to control power quality. As observed [41] the output from the renewable energy sources is always variable in nature. This necessitates inclusion of interface like grid synchronized inverters, in order to synchronize and control the renewable energy sources to the grid [2]. To achieve grid synchronization, the most popular grid synchronization method Phase Locked Loop (PLL) is used. Other techniques for synchronization include detecting the zero crossing of the grid voltages or using combinations of filters coupled with a non linear transformation. When Wind in the renewable resource, in this case the main conditions which must be met for its smart grid integration can be accounted: the wind power frequency should be at par with the grid frequency; the terminal voltage magnitude must match with the grid, the phase-sequence of the two three-phase voltages must be same and the phase angle between the two voltages must range within 5 percent [30].

III. CONGLOMERATE CHALLENGES IN RENEWABLE ENERGY SMART GRID INTEGRATION

There are a variety of considerations when high levels of Variable Renewable Energy are integrated to smart grid system. This section discuss challenges based on operational considerations -

1. **Geographic diversity of variable resource-** The effects of geographic distribution of renewable energy power plants (WPPs) on the reliability of electrical output cannot be denied as these sites are then organized, on the basis of nearest neighbors, into networks ranging from single renewable Power Plants integrates forming full network of various renewable power plants. For each network, a suite of statistics is computed and used to characterize energy reliability and the area enclosed by, the network [9]. It is an observation as we spread the Variable Renewable Energy across different areas there is a marked decline in the system-wide variability. Numerous studies have examined how the system-wide variability is reduced for both wind and solar [38].
2. **Renewable forecasting-** Accurate forecasting of renewable energies such as wind and solar has become one of the most important issues in developing smart grids. Accurate forecasting of VRE output can significantly reduce reserve margins and ensure the most economic systems [1]. Therefore introducing suitable means of weather forecasting with acceptable precision becomes a necessary task in today's changing power world. New forecasting techniques have shown increased value beyond persistent forecasting and the value of renewable forecasting has been studied for integrating higher penetrations of VRE [46].
3. **Generator flexibility-** Generator flexibility is defined as the ability of the generator to response a balance between the powers up and down. It is also based on its ability to operate at low output levels. Generator flexibility is important consideration when trying to balance load and available generation where large amounts of variable renewable resources are being integrated in s Power System [9].
4. **Energy Storage-** The basic concept of smart grid is any amount of production or consumption can be co-ordinate at any location in the power system provided the difference between these two lays within a certain band. The balance between production and consumption depends on the transfer capacity of the

system. The situation can be more complicated in integrated renewable energy – smart grid meshed systems [23]. A "smart grid" that can control, or influence, both production and consumption would allow more of both to be integrated into the power system. To accomplish this goal, communication technology plays an important role [23] encourage changes in production (i.e. generator units) and consumption (i.e. customers or devices).

Different methods are available to balance consumption and production like **Physical energy storage**, for example in the form of batteries or pumped-storage hydro. **Virtual energy storage, can be done** by shifting energy consumption pattern. For example charging of car batteries this step can also be used for cooling or heating loads. However, this approach does not result in energy saving, but adds to more efficient use of the generation facilities and the power system transport capacity here the total energy consumption may be reduced with reduced losses like reduced average temperatures with heating systems, and the ability to use more efficient forms of energy. To balance the smart grid one can also choose [21] **Load shedding**, done when the load is removed from the system when all other methods fail. Accepting the occasional small amount of load shedding may save large investments in the power system especially in developing countries where, uncontrolled and inadvertent load shedding often occurs automatically during grid or generator overload. Though it is not the kind of application that is normally considered in the discussion on smart grids but in primitive years of developing this technology it can be used. For renewable resources the primary energy is usually transformed into electricity whenever it is available. But if generation exceeds consumption, renewable sources may be turned off also called **Curtailment of production** [16].

5. **Renewable Energy Pricing-** Renewable Energy Pricing acts as a significant variable in success of renewable energy integrated smart grid though many times it is based on primitive pricing models which were used for renewable energy. As the smart grid technology is evolving it aim should be to provide electricity consumers opportunities for better utilizing electric system assets so to satisfy consumer energy demands at the rate of lower monetary and environmental cost [31]. It is to be noted when selecting the electricity tariff consideration like marginal cost, load pattern, social criteria and revenue requirement of the power utilities are taken into account where Marginal costs is the incremental costs which is a result of appropriate adjustment made between the power generation and distribution systems to meet the continuously increasing demand per unit. **Marginal costs** in the power sector can be divided into four levels namely generation, transmission, distribution and retailing. **Renewable energy pricing** depends on the Load pattern, which is set according the Time of Use (TOU) rate [10]. Pricing is done to encourage balance the power consumption pattern and control wastage. Setting **Revenue requirement of the power utilities** the power utilities need to scrutinize their financial status and estimate average electricity tariff that would yield the financial status pursuant to an established criteria. The challenge doubles up when variable renewable resources are integrated in the system due to its non uniformity. In order to estimate the financial status, explicit assumptions are essential like cost of spinning reserves, natural environment supporting growth, inflation rates or consumer price index, efficiency improvement of the transmission system, distribution system and retail business etc. **Social criteria** is the key that will determine the future of smart grid it can be political as well as social, how a government of a country is interested in upbringing changes to ensure sustainable practices and efforts it is undertaking [19], subsides given, projects being launched. Thus these factors need to constantly be matched for better renewable integration with the smart grid network.

6. **Sustaining Security and Reliability for Smart Grid Business Services-** Smart grid communicates with central SCADA systems to enable operators to take action on information which collect by intelligent sensor in customer sides. [39] Here the vulnerabilities regarding data network securities can fall due to Poor Network Protocol Implementations which Lacks input validation like Buffer overflow in Control System service or due to Lack of bounds checking in Control System service. It can also arise if the Control System protocol uses weak authentication or if the Control System product relies on standard Information Technology protocol that uses weak encryption. Network Design Vulnerabilities can occur due to Lack of network segmentation or when the Firewall is bypassed. Similarly,[14] Network Component Configuration Vulnerabilities occur when access to specific ports on hosts is not restricted to required IP address or when the port security is not implemented on network equipment.

IV. CONCLUSION

Renewable energy source integration with power systems is one of the main concepts of smart grids. One of the key aspects in smarter grid applications is to have ability which makes it possible to operate the power system on both the supply-side and the demand-side [50]. Due to the variability and limited predictability of these sources, many challenges arise when integrating them with smart grid. These challenges may slow down the implementation of the Smart Grid or if they are not properly resolved, they may impede the full utilization and realization of the futuristic Smart grid. Integration of renewable sources in power system with their variable generation schedules introduces certain challenges in the systems. It will necessitate the changes in power system planning and operation while keeping reliability and economy constraints in considerations. Large-scale storages also need to be incorporated to meet peak loads demands. There are several factors that need to be addressed during integration like power quality, reliability, energy conversion cost and power system efficiency. Research and development regarding these issues should be encouraged so develop methodologies and algorithms in order to meet these challenges and make the power grid transition towards smart one in an effective manner.

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