Performance Analysis Methods in Smart Grids: An Overview

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ABSTRACT

This paper presents an overview of the performance analysis methods available for the Smart Grid (SG). Increased energy demand, volatile energy costs, uncertain power generation from the renewable energy resources (RERs), electric vehicles, and environmental concerns are coming together to change the nature of the traditional power grid. Many utility companies are now moving towards the smart metering and the Smart Grid solutions to address these challenges. Smart Grid is inclusive of advance tools, latest communication technologies and storage devices, which makes the Smart Grid vulnerable and complex. This paper aims to review the performance analysis of Smart Grid. It also presents various models of the Smart Grid performance indices. It presents the methods available for stability, reliability and resilience assessment in Smart Grid. It also describes the implementation approach using the real time tools and techniques.

Keywords: Performance analysis, Renewable energy sources, Reliability, Smart grid, Stability, Smart metering.

1. INTRODUCTION

Smart grid (SG) is a power grid which utilizes communication systems, and power and energy technology to enhance the efficiency, reliability, economics, and sustainability of electric power systems [1]. It is considered as an ultimate solution to the challenges that are emerging from the increasing electricity demands, subsequent increase in the pollution, and the outmoded power grid infrastructure [2]. Different smart grid networks can be banded together to create what is commonly called a system of systems. Each network group has a set of resources that it applies to electric generation, transmission, and distribution tasks. Each of these systems can pool their resources and capabilities to create more complex systems. This approach has the effect of creating a high-level entity that has more flexibility, functionality, performance capability, and resiliency. Renewable energy resources (RERs) becomes more prominent in the world electricity market because of the increased demand for electricity generation, the deregulation of the electric power industry, the requirements to reduce CO_2 emissions, etc. For solving future energy problems, it is expected that two major technologies will play a vital role: (i) Replacing the conventional fossil fuel based sources by RERs such as wind, solar, tidal, and hydro for electricity production. (ii) Use of highly efficient, reliable power electronic converters in generation, distribution, and load end systems. With the advent of power electronics converter with sophisticated control strategy, renewable energy systems are largely interconnected with grid network for power feeding. Especially, wind and solar PV systems are highly contributing for future energy generation. In recent years, Smart Grid technologies such as Advanced Metering Infrastructure (AMI) and Distribution Management Systems (DMS) have created remarkable opportunities for distribution grids in terms of operation, control and optimization.

Reference [3] proposes an approach to the random access procedure within Long Term Evolution Advanced (LTE-A) for the calculation of the average overall delay, by considering multiple classes of Machine-to-Machine (M2M) devices with diverse Quality-of-Service (QoS) requirements. In Reference [4], multiuser selection approach is used in dynamic home area networks (HANs) for Smart Grid communications, to reduce the effects of fading at receiver part of smart meter. An experimental study of grid connected solar photovoltaic (PV) energy system and the performance analysis under real meteorological conditions with a web-based monitoring procedure applied to the grid connected solar PV system is presented in [5]. A modeling and validation method based on the colored Petri nets (CP-nets) which allows for the development of a generic model representing the overall behavior of the different components of Smart Grid is presented in Reference [6]. Reference [7] studies the performance of M2M communications in LTE-A networks. The simulation results of the DNP3 communication protocol over a TCP/IP network, for Smart Grid applications are proposed in Reference [8].

Reference [9] presents an intelligent energy harvesting and traffic flow forecasting for plug-in electric vehicles in a vehicle-to-grid environment. Various data processing architectures for the hierarchical power distribution networks is presented in [10]. Ref-

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erence [11] presents a common methodology to study the impact of energy storage devices on energy systems by modeling them as electric circuits in simulations. Reference [12] describes the communication requirements for monitoring energy transmission in smart grid by wireless enabled overhead line sensors and the feasibility of using Zigbee communication for the overhead line monitoring application. A real-time co-simulation platform for analyzing the power grid operation, taking into account the integrated communication systems is presented in Reference [13], and it also describes how a co-simulation platform can be set up using OPNET as communication and OPAL-RT as power system simulator. Reference [14] is focused to disclose in a clear way that what Smart Grid is and what kind of communication techniques are used. Reference [15] aims to review the main requirements of two important Smart Grid adaptive energy conservation and optimization solutions called conservation voltage reduction and volt-VAR optimization, in terms of control, measurement, communication and standards for grids. Reference [16] demonstrates how false data injection attacks can be constructed blindly, i.e., without system knowledge; including the line reactance and topological connectivity information. Reference [17] compares the performance of transmission control protocol (TCP)-Reno and TCP-Vegas variants when handling sensory and metering traffic.

With wide range of applications of Wide Area Monitoring System (WAMS) based on phasor measurement unit (PMU) technology, model estimation using output only responses has drawn great attention of many researchers. The main benefits of wide area protection and control are the improved system operation and planning, increased power transfer capacity, optimum use of existing equipments, lowered risk of power system instability, and the reduced impact of disturbances. As the utility industry concentrates on the complex and ambitious transformation of outdated power grid to the new Smart Grid, it has struggled to develop a shared vision for the smart grid end-state and the path to its development and deployment. Recently, the Smart Grid attracted the focus of many researchers, utilities, power industry and others, as it includes the latest devices from advanced controls, sensors, communication and many more. Moreover, the full-fledged working of Smart Grid will involve customers as well. Therefore, it attracted the attention in the recent years. However, the Smart Grid still needs improvements and these improvements should be tested on small scale and their results should be evaluated through simulations and random tests. The real time co-simulation platform can be set up by using the OPNET (communication simulator) and by using the OPAL-RT (power system simulator).

The remainder of the paper is organized as follows: The determination of performance indices for Smart Grid is presented Section 2. The data processing architectures for Smart Grid is described in Section 3. Section 4 presented the performance analysis of Smart Metering. Stability, reliability and resilience assessment in Smart Grid is presented in Section 5. Section 6 presents the description of design and implementation of Smart Grid testbed. Finally, the contributions with concluding remarks are described in Section 7.

2. DETERMINATION OF PERFORMANCE INDICES FOR SMART GRID

Power flow and optimal power flow (OPF) are used for the evaluation of system performance in power system. The load flow or OPF are used to determine the state of the power system under a given operational condition and to allow the operator to detect the overloads and to evaluate the transfer limits. Contingency Analysis is also used for performance evaluation. The information obtained through the load flows provides voltage and phase angle information at each end of the node [18]. It is used to check system health at any time and at any point in the system.

The load flow studies improve the planning and operation of power system [18]. Especially, in the case of transmission planning, major benefits can be obtained through the load flow studies. The performance of the system is evaluated using different contingencies such as loss of line, loss of transformer, loss of generator, etc. It can also be checked for different loading conditions, especially under no load and peak load conditions, so that we can find out maximum and minimum values for the design of system components. The load flow in Smart Grid environment should satisfy the following questions [18]:

- What are the computational needs of an SG?
- What are the qualities and characteristic of an SG?
- What are the new features of power flow/OPF for the performance and evaluation of an SG?
- What changes are required to make self adaptive power flow to new design?
- How can load flow adapt real time (RT) inputs and give RT outputs?
- How to carry out results in the presence of uncertainty and randomness in the system?

The new load flow and OPF should include the following features [18]:

- It should include Center Generation (CG), Distributed Generation (DG) and co-generation.
- It should be effective for both local and global control.
- It should be adaptive to the conventional equipments and new changes with proper co-ordination.
- It should be able to evaluate the randomness and uncertainty present in the system.

- It should be dynamic.

To enhance the existing grid load flow capabilities, the Smart Grid load flow should consist the following essential components [18]:

- Data acquisition for mesh or radial networks.
- Solution of power balance equation available for the voltage angle and magnitude values.
- Existence of connection of data to assure feasibility of the network.
- Y-bus formulation representing the interconnection of the system under study and the initial conditions determination.
- Solution of active and reactive power mismatches and then checking the mismatch by adjusting the initial conditions.
- With the snapshot power demand, a feasible static voltage and angles are determined to minimize the mismatch.

With the increasing levels of penetration of Renewable Energy Resources (RERs), the grid parameters involve stochasticity and randomness. Moreover, the load demand pattern is always random and unpredictable. Therefore, with this new environment, the Smart Grid has to sustain its operation efficiently. It is possible only with new load flow and OPF techniques. Therefore, the new power flow and OPF should be dynamic, and it should be applicable to real time applications. In the literature, the methodology suggested by various researchers is directed towards the next generation optimization techniques such as Stochastic Programming (SP), Adaptive Dynamic Programming (ADP), Mixed Integer Non-linear Programming (MINLP), Evolutionary Programming (EP), meta-heuristic algorithms, etc. These methods are capable of solving the randomness involved into the system.

Nowadays, the smart grid maturity model (SGMM) is helping the industry to overcome these challenges by presenting a consensus vision of an SG, the benefits it can bring and the various levels of an SG development and deployment maturity. SGMM is helping numerous utilities worldwide develop targets for their smart grid strategy, and build roadmaps of the investments, activities and best practices that will lead them to their future an SG state. The strategic uses of SGMM are,

- Plan for regulatory, technological and organizational readiness.
- Establish a shared vision for the Smart Grid special features.
- Communicate and evaluate the Smart Grid vision, both internally and externally.
- Use as a strategic framework for evaluating smart grid business and investment objectives.
- Benchmark and learn from others and relative improvements.

The structure of SGMM structure is based on three fundamental concepts, they are,

- *Domains* : Eight logical groupings of functional components of an SG transformation implementation.
- *Maturity Levels* : Five sets of defined characteristics and outcomes.
- *Characteristics* : Descriptions of over 200 capabilities that are expected at each stage of an SG journey.

3. DATA PROCESSING ARCHITECTURES FOR SMART GRID

The distribution power network is divided into various sub-grids, which forms a hierarchical topology. The major components of architectural model of Smart Grid are presented in detail in Reference [19], and they are:

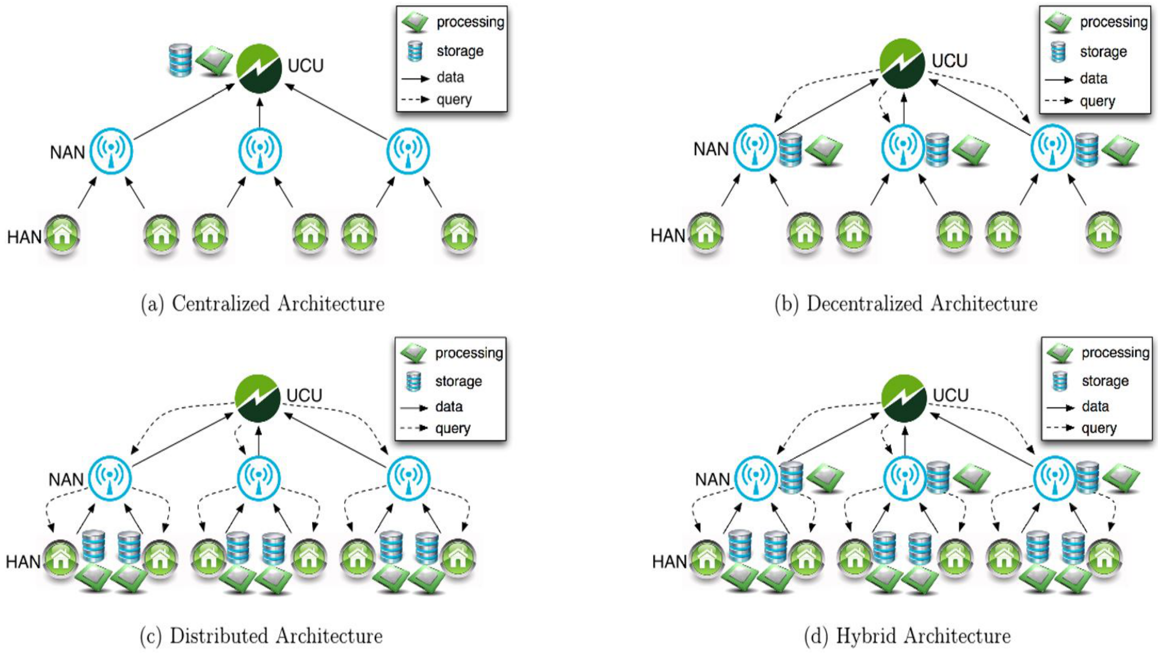
- *Home Area Nodes* (*HANs*) : This is the node at the consumer/customer premises which receives all the energy consumption information in the house.
- *Neighborhood Area Nodes* (*NANs*) : This node acts as an intermediate node between the customers and the utility, and serves a small neighborhood area.
- *Utility Control Unit* (*UCU*) : This unit is responsible for maintaining data, billing, carrying out the demand response management, and determining the electricity price.

The detailed descriptions of various data processing architectures for Smart Grid are presented in References [19-20]. Figure 1 depicts the various data processing architectures for the SGs.

From this figure, it can be observed that there are 4 different architectures, and they are centralized, decentralized, distributed and hybrid architectures. From Figure 1(a), it can be observed that the centralized architecture, only UCU has storage and data processing capability. From Figure 1(b), it can be observed that only NANs have data processing and storage capability. In the distributed architecture, all the HANs have data processing and storage capability, and this can be seen from Figure 1(c). Whereas, in hybrid architecture, both NANs and HANs have storage and data processing capabilities, and this can be seen from Figure 1(d). The evaluation of these architectures on rural and urban environments has been presented in Reference [19].

4. PERFORMANCE ANALYSIS OF SMART METERING

Smart Grid is an intelligent power distribution system that uses information and communication technology (ICT) to enhance reliability, efficiency and sustainability of power generation and distribution network. Smart Grid can be considered as an ensemble of several applications such as demand forecast, demand response, anomaly detection, emergency management and adaptive pricing, built upon



(a) Centralized Architecture

(b) Decentralized Architecture

(c) Distributed Architecture

(d) Hybrid Architecture

Fig.1: *Various data processing architectures for SGs [19].*

an Advanced Metering Infrastructure (AMI) - a system that collects, measures and analyzes data about the energy usage [19]. The overwhelming data generated by the Smart Meters (SMs) requires information management mechanisms for large scale data processing and storage [19].

SM is a high functionality electric power meter which collects the data about the power usage and automatically reports the volume of consumption to the power supplier. The data that the SM collects is used to monitor in real time (RT) when consumers are using electricity and how much it costs. Presenting this information in a visualized format can contribute to consumers using energy more efficiently [21].

The smart meter is composed of metrology integrated circuit, host interface, communication media, and user privacy and security [22]. From the security and communicational point of view, an AMI is considered to include the home area network (HAN), smart meter gateway (SMGW), neighborhood area network (NAN) and wide area network (WAN). The detailed description about these networks is presented in Reference [22]. However, the passwords protection schemes and basic encryption techniques for the smart meters requires device authenticity, data confidentiality, data authenticity and integrity, and consumer privacy and security [22]. The SMs collect data from the end consumers and transmit this information through the Local Area Network (LAN) to the data collector. This data transmission process is executed in every 15 minutes or based on the data requirement. Then, the utility central collection points further processes the data by using the Wide Area Network (WAN). By using the two way communication, the signals can be sent directly to the meters and the distribution devices [23].

The traditional analog electronic and electromechanical meters are easy to attack, steal power and manipulate power consumption details. However, by using the smart meters, one can detect and minimize the theft of electricity. The attacks on smart meters are classified as physical attacks and the cyber-physical system attacks. Various attack prevention schemes, i.e., false-data attack prevention, man-in-the-middle attacks prevention, and denial-of-service attack prevention schemes are described in Reference [22]. Smart meters offer the customers to estimate their electricity bills from the collected data, and hence they can manage their energy consumptions to reduce their electricity bills. By using the smart meters, the utility companies collets the information to realize the real time pricing, so that the companies can limit their maximum energy consumption and tries to encourage users to reduce their demands in the peak load periods [23].

5. STABILITY, RELIABILITY AND RESILIENCE ASSESSMENT IN SMART GRID

5.1 Stability Assessment

Voltage Stability can be defined as the ability of the power system to maintain acceptable levels of voltage at all system buses during normal operation and regain an acceptable operating point after being subjected to a disturbance. The stability of a power system however is impacted by the new smart grid technologies that are introduced to traditional power grids. Voltage instability is linked to the inability of the combined generation-transmission system to provide the power requested by loads, as a result of equipment outages and limitations of reactive power generation. Most of the works on voltage stability assessment of power systems has concentrated on offline studies. However, with the advancements in Phasor Measurement Unit (PMU) technology, it is quite possible to assess voltage stability margin of real time systems in smart grid.

RERs and energy storage devices have a great impact on the voltage stability of the power system. The intermittent nature of renewable sources cause voltage fluctuations in the system and may result in power oscillations. Smart grid technologies offer new solutions for monitoring and controlling the grid's transmission network. PMUs are capable of taking measured samples of voltage and current, that are time synchronized via global positioning system to the Universal Time, in as many as sixty time frames per second, giving a snapshot of the smart grid in real time.

The dynamic voltage stability indices can be developed with the help of Phasor Measurement Unit (PMU). PMU provides real time information about voltage and phase angle at every 30 seconds through a waveform generation. This waveform can be converted into real numbers with the help of pi systems. OSIsoft is one of the software that converts this signature information into number. Achieved numbers can also be verified through state estimator, and it will eliminate bad data if any present in the system. Therefore, the achieved numbers can be used for the voltage stability indices calculation. Suppose, if the PMUs are not installed, then any optimization technique can be used to generate the missing data using the meta-heuristic algorithms. After creating the data, it is used to determine the Voltage Stability Indices (VSI) calculation. The generated VSI will be dynamic and gives real time information about voltage stability. It's value is between 0 and 1. If the value is close to 1, then the system is more stable. VSI is the measure of how far is the system from instability

In Reference [24], the impact of smart grid technologies on power system voltage stability has been considered. Renewable energy sources and energy storage devices have a great impact on the voltage stability of power system. References [25-27] have investigated the impacts of renewable sources namely, solar farms and wind farms on system stability. An approach for the stability assessment of a smart power system, i.e., betweenness index which is based on ideas from complex network theory is presented in [28]. A critical switching flow concept as a transient stability index to assess system transient stability associated with topology control is proposed in [29].

5.2 Reliability Assessment

There are many terms used in reliability discussions, including security, resiliency, risk, robustness, and vulnerability. Reliability is used to encompass all of these, representing an average or expected level of service provided by the system over a time period. Two-way flow of energy and communications in the Smart Grid enables new technologies to supply, deliver and the use electricity. Smart Grid initiatives are achievable through the use of information infrastructures that feature peer-to-peer monitoring, communication, protection and automated control. The analysis of Smart Grid operation requires considering the reliability of the cyber network as it is neither invulnerable nor failure free. A quantitative evaluation of reliability of modern power system incorporating the impact of cyber network failures on the reliability of the power network is proposed in Reference [30]. A new approach for the reliability assessment of future power distribution systems affected by the customers' distributed energy resources is presented in [31]. Some reliability considerations are [32-33]:

- Cyber security in design, planning and operations.
- Ability to maintain frequency and voltage controls.
- Device interconnection standards.
- Increased reliance on distribution level assets to meet bulk system reliability requirements.
- System inertia-maintaining system stability.
- Coordination of controls and protection systems.
- Disturbance ride-through.

The reliability theory application is used for the dependability of the Smart Grid. Reliability approaches provide an important analytical tool that is used to evaluate and compare Smart Grid design and performance. Reliability parameters vary from situation to situation or from component to component. For the power system reliability analysis, the transition rates should not be constant for the considered time period, but they will change from time to time according to the weather conditions, as the power system faults and their repair time are related to environmental conditions [32]. The distribution systems reliability is dependent on many variables like load capacity, customer base and maintenance, as well as type and age of equipment. Reliability analysis is stochastic and predictive in nature. The aim of distribution system reliability tool is to provide accurate, consistent comparisons between competing design options. Most of the utility companies and regulatory bodies describe the reliability of the distribution and transmission circuits in terms of simple and transparent reliability indices [34]. These indices are:

- *System average interruption duration index* ($SAIDI$) : It is the sum of all outage durations/number of customers. SAIDI is average duration of extended outages experienced by all

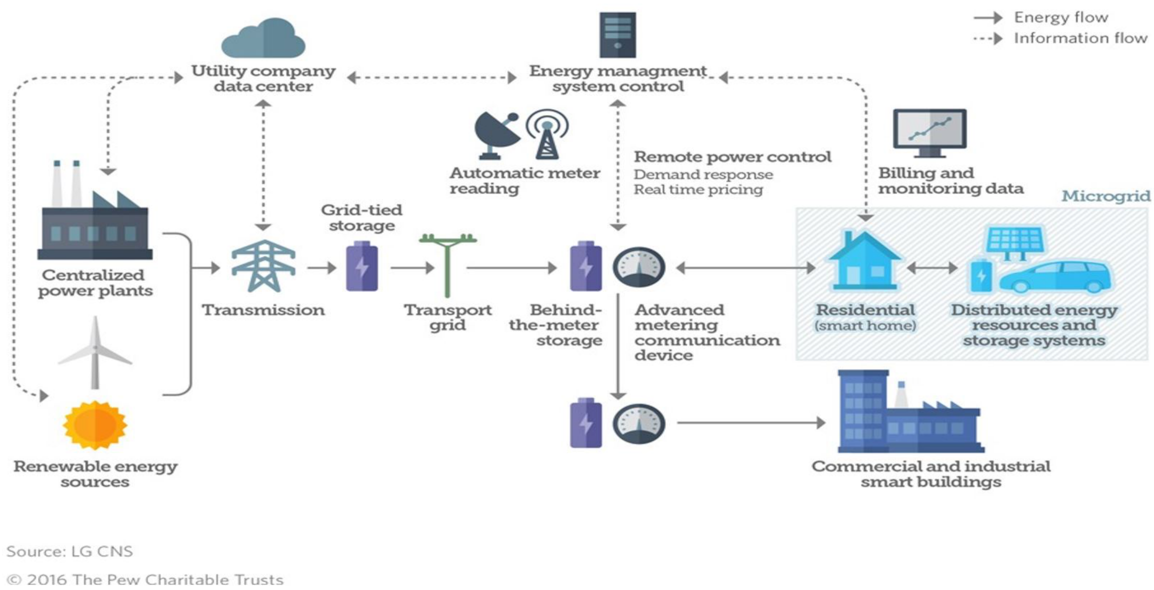


Fig.2: *Schematic Diagram of Smart Grid with Energy and Information Flows.*

customers over a given time interval (generally a year). It is the average duration of outages per customer for the system as a whole. It evaluates the utilities' performance after a sustained power interruption. It is represented in hours and minutes [35].

- *System average interruption frequency index* (*SAIFI*) : It is the count of all extended outages/number of customers. SAIFI is average frequency of interruptions that customers experience over a given interval, generally one year. It is represented as a rational number.
- *Customer average interruption duration index* (*CAIDI*) : It is SAIDI/SAIFI. CAIDI is average duration of an interruption for those customers who experienced interruptions. It is expressed in hours and minutes.
- *Momentary average interruption frequency index* (*MAIFI*) : It is the count of momentary outages/ number of customers. MAIFI is average frequency of momentary outages. It is expressed as a rational number.

Figure 2 shows the schematic diagram of Smartgrid with energy and information flows.

5.3 Resilience Assessment

Resilience is the property of a material to absorb energy when it is deformed elastically and then, upon unloading to have this energy recovered [36]. Ensuring resilient operation and control of smart grids is fundamental for empowering their deployment, but challenging at the same time. Grid resilience is a key attribute of the future of the grid. Self healing of a system is that uses the information, control, sensing and communication technologies to allow it to deal with unforeseen events and minimize their adverse impact. Resilience refers to the ability of a system to recover from a failure after it has occurred [37]. Resilience is closely related to restoration, which is the process of restoring a power grid after a blackout. Reference [38] characterizes and analyzes the resiliency of Smart Grid communication architecture, especially, RF mesh based architecture, under cyber attacks.

Reference [39] proposes various techniques that are analyzed and evolved continuously to meet the new challenges as they emerge. A review of the state of metrics for the resilience of natural gas, electric power and oil distribution systems revealed that the metrics generally are not standardized, consensus on core required capabilities and how to measure those capabilities for resilience to extreme events is lacking, and relating capabilities to desired outcomes is not well understood [40].

5.4 Smart Grid Protection Issues

The existing grid structures have significant drawbacks, such as manual fault detection, independent voltage regulation, non-optimized power flow, and limited power management. Besides, such conventional grid infrastructures are extremely dependent on each other. Hence, a fault or any other undesirable event that occurs in any location of the grid can rapidly affect a huge part of the system and this problem may cause more damage to the total grid. In order to solve this problem, the disadvantages of grids must be eliminated and improved grid solutions must be implemented. Smart grids offer some technological developments to improve the grid, such as real-time fault detection, remote switching, real-time power management, and dynamic simulations for minimizing losses. With the purpose of detecting possible faults and finding rapid solutions, a reliable communication system is needed, which is available in the smart grid concept to support the data acquisition, protection, and automatic control of the smart distribution grid [41].

Another important benefit of smart grids is the effective selectivity issue that is significantly important at the time of fault events in the system protection. It will be possible to prevent extension of faults to large areas of a grid with a short response time. This can be achieved by fast protection and remote control systems. Through the advanced measurement, protection, and communication features of smart grid structures, automatic fault detection and insulation can be performed easily. There are several options to define the selectivity concept in order to ensure continuous supply of energy to customers once the location of the fault is detected. After isolating the fault location from the grid by using breakers, the consumers that are not fed will be powered by other sources in the grid [41].

6. DESIGN AND IMPLEMENTATION OF SMARTGRID TESTBED

Reference [42] describes an SG testbed for the study and development of Wide Area Monitoring and Control (WAMC) systems. The developed test-bed consists of a physical emulation of a power system, ten Intelligent Electronic Devices (IEDs) with integrated PMUs, a Phasor Data Concentrator (PDC) and user interface for data acquisition and control connected via a local area network. The testbed has the capability of testing and analyzing the performance and the security, both cyber and physical of WAMC applications. The developed testbed should incorporate a system-wide solution that reduces the cyber and physical vulnerabilities, minimal impact on performance and rapid recovery from disruptions. An evaluation criteria for the evaluation of implemented test bed, and experiments are designed in [43] to evaluate the test bed according to the defined criteria.

Smart Grid allows two way communications for the real time measurements, and many researchers have discussed about the real time pricing by either taking access of consumer energy consuming equipment or by spread awareness about peak time usage and its disadvantages. The former way is may not be applicable in practice; however, the later way allows the dynamic pricing. The hardware required for developing the Smart Grid testbed is the RERs such as wind energy generators, Solar PV modules, main grid/3 phase AC supply, microcontroller, inverter, converter, smart switches, 3 phase AC Load, DC Load, etc. By using the Smart Grid test bed, various power system studies can be performed such as to carry out the Locational Marginal Pricing (LMP) studies, optimal generation problem, RERs can be tested under different loading conditions and contingencies, to evaluate the reliability of the system with and without the storage systems, to carry out the cost-benefit analysis, etc.

The objective of distribution automation is the real-time adjustment to the changing load demands, generation, and failure conditions of the distribution system, without any operator intervention. The distribution automation devices are evolving to be more reliable and robust, act as a source of planning data, and offer higher computing power. In the presence of distribution automation devices such as RTUs, PMUs, EMS, SCADA and smart meters into the system, one can determine different real time indices (such as reliability, vulnerability, sustainability, resiliency, voltage and angle stability, etc.

Various simulation tools available for the power system analysis are PowerWorld, OpenDSS, Simulink, RTDS and OPEL-RT. The available communication system simulators are Network Simulator versions 2 and 3 (NS2/NS3), OMNet++, OPNET modeler. The software tools required to assess the performance of Smart Grid are [43-44],

- *General Algebraic Modeling System (GAMS)* : It is a high-level modeling system for mathematical optimization. GAMS is designed for modeling and solving linear, nonlinear, and mixed-integer optimization problems (used for the probabilistic studies).
- *OPNET* : It is a simulator tool used to simulate the performance and behavior of any type of network.
- *NS2/NS3*, *OMNeT++* : Communication and network simulator.
- *OPAL−RT*, *PowerWorld*, *MATLAB(Simulink)*, *GridLAB − D* : These are the power system simulators.
- *PSS/E* : It is used for the power flow, OPF, fault and reliability studies.
- *ETAP* : It is used for fault and reliability studies.
- *NS2 cooperated with ADEVS(A Discrete Event System simulator)* : It is used to simulate the communication delay on power system monitoring and control.
- *Geographical Information System (GIS)* : This tool is used for the maintenance and reliability of the distribution network. GIS is the real time application that can help in the measurement and control of Smart Grid. The information obtained through GIS can be extended to the fault centers and physical faults can be minimized and solved very quickly. The GIS can help to maintain the reliability of the system.

7. CONCLUSIONS

This paper has presented an overview of the performance analysis tools/approaches for the Smart Grids (SGs). The power flow and optimal power flow (OPF) modules are discussed by incorporating the renewable energy resources (RERs) for the performance and evaluation of Smart Grid. This paper evaluates the reliability, resilience and stability indices for performance measure of the Smart Grid. This paper discusses the data processing architectures and smart metering performance analysis. Various real time measurement tools and their applications in measurements and control of Smart Grid are discussed in detail. Finally, this paper also presents the discussion on the design and implementation of Smart Grid.

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