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Analysis on Emerging Trends and Challenges in Smart Grid Automation Technology from Generation to Distribution

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Power System or Grid is defined as the collection of group of devices, components that make a physical system to generate, transmit and distribute electricity to *the end users. Complexity of power system has grown tremendously in the last few decades, facing new challenges during its operation. In order to meet some of these challenges there is a definite need of automation which helps in automatically operating & controlling the power system under various circumstances. The new era of smart grid in the 21st century has made automation really a need to operate grid under the dynamics of rapid load changes, makingthe system more time sensitive towards faults and failure modes. Automation being one of the critical components in realizing smart grid, this paper tries to present an overview of grid automationtechnology trendfrom generation to distribution over the past few years andfuture opportunities& challenges.*

Key Words: *Automation, Generation, Transmission, Distribution, Smart grid, Trends, Challenges*

1.0 INTRODUCTION

Power system or Grid automation is defined as the act of automatically controlling the operations of the grid using state of the art instrumentation & control, data acquisition, and communication technologies [1]. Power system automation includes processes associated with the generation, transmission, distribution and utilizationthat generate electricity, transmits and distributes it for end user applications and needs. Hence grid automation can be further classified into generation automation, transmission automation and substation automation/distribution automation blocks making it more decentralized in order to focus more on corresponding sector applications and meet its own challenges. More details about each automation block are explained in further sections. Initially when every vendor used to have their own proprietary technologies for automating the systems were non-interoperable and hence need for standardizationandstandardshas evolved as shown in Figure 1, as a need for a smart grid.

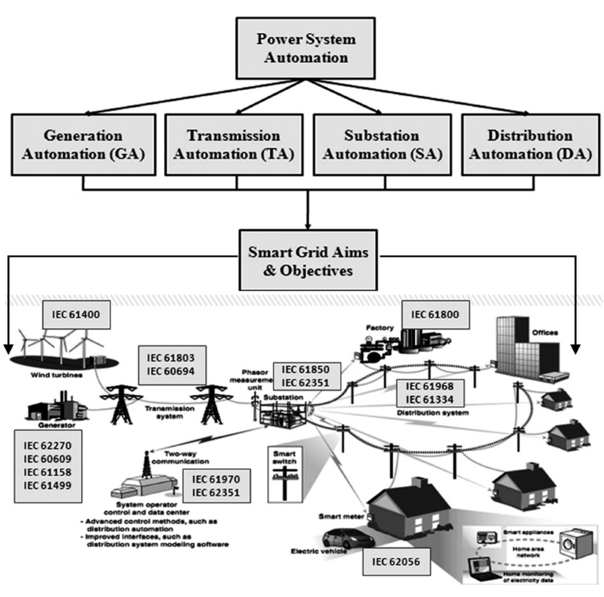

FIG. 1 AUTOMATION CLASSIFICATION & STANDARDIZATION

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The IEC technical committee [2] has come up with a set of standards to make systems interoperable, as the major benefit of automation can be realized only by proper co-ordination between grid supervision, protection, monitoring and control components in a standardized manner. These various standards fit at various component levels of power system and enable it to operate in a more rigid, efficient, automatic and reliable manner, with some standards being specifically on automation. Hence automation with standardization has become a critical part of the smart grid interoperability requirement.

The description of each standard [2] is given below :

IEC 62270 – Hydro Electric Power Plant Automation

IEC 61400 – Wind Turbines

IEC 60609 – Turbines

IEC 61158 – Field Bus Automation

IEC 61499 – Distributed Control & Automation

IEC 61803 – HVDC Transmission

IEC 61970 – Energy Management Systems

IEC 62351– Data andCommunication Security in Power System

IEC 60694 – HV Switch Gear

IEC 61850 – Substation and Feeder Automation

IEC 61968 – Distribution Management Systems

IEC61334 – Reliable PLC Communication for Distribution

IEC 61800 – Power Electronic Drives

IEC 62056 – Metering Automation

The major motivation behind writing this paper is, to present higher level approach and analysis on major functions of grid automation with overall "systems perspective" at a glance across entire power system (grid), starting from generation to distribution automation systems. The technology trend & key applications of grid automation in the last few years, stepping towards smart grid, and various future opportunities & challenges are discussed in a consolidated, simple & efficient manner which is missing in today's literature on smart grid.

Further this paper is organized as, Section 2 gives brief overview of smart grid automation aims & objectives, Section 3 on grid automation technology view, Section 4 discusses emerging major technology trends in generation, transmission, substation and distribution automation over the last few years that realize some of the smart grid objectives, Section 5 provides conclusion and finally Section 6 discusses some of the future opportunities& challenges in smart gridautomation.

2.0 SMART GRID AUTOMATION OBJECTIVES

Smart Grid which is defined as "smart + electricity grid" is an extension of the 20th century power grid by adding advanced communication and information technology infrastructure enabling two-way data transfer for efficient operation of grid to meet various challenges in 21st century[3]. The major aims and objectives of today's smart gridspecific to automation are,

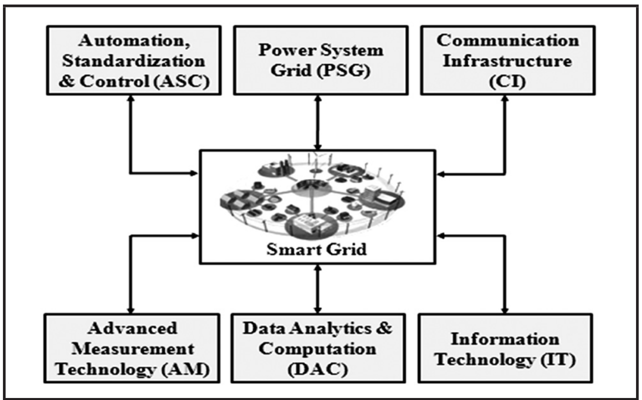

FIG. 2 SMART GRID COMPONENTS

a) Automatic self-healing capability following power system disturbance events (detect incipient problems, minimize impact of fault events).

b) Achieve standardization and interoperability.

c) Automatic demand management and control with customer participation.

d) Operating resiliently against physical and cyber-attacks (blackouts, forced outages etc.)

e) Providing high degree of power quality & reliability.

f) Ensuring stability, integrity and synchronism across the network 24x7.

When we look at these goals, they are achievable by incorporating advanced communication and computation technologies, in which automation plays a critical role. Automation is not achieved just by eliminating human interventions or automating maintenance, configuration and operation of the grid but by providing self intelligence capabilities to protect, control and operate the grid more resiliently, in which automation algorithms play a key role in analyzing various conditions using time critical data, information and develop strategies to any events or alarms that occur during power generation, transmission, distribution, and consumption. Clearly, smart grid provides an integrated platform for various technologies to operate the system in a safe, reliable, efficient, clean, secure, sustainable and resilient manner. The major building blocks of a smart grid for reference are shown in Figure 2, of which definitely automation is a critical segment as discussed earlier.

3.0 SMART GRID AUTOMATION VIEW

Automating a power system or grid can bring substantial benefits to the operators and end-users by improving system reliability, planning, design, efficiency and response to various failure modes that may occur during day-to-day operations, which matches with some of the smart grid objectives. The availability of technology for automation has grown significantly over the past few years. Several challenges led to the birth of power system automation of which system growth, availability, reliability, engineering, planning expectations and most importantly smart grids are the key ones. As the system growth continues and expectations rise due to the tremendous growth of industrial and commercial consumers, it will demand even further automation of the system.

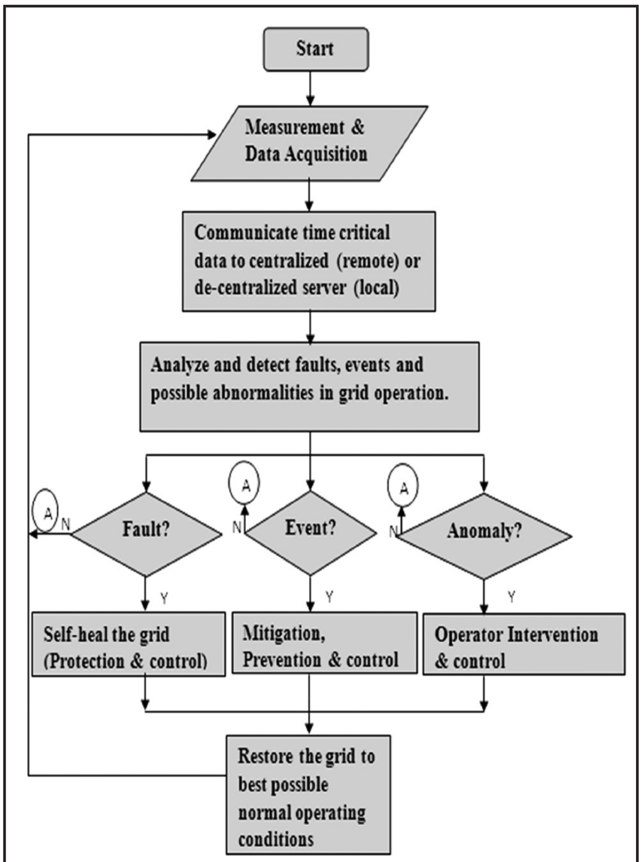

FIG. 3 GRID AUTOMATION ALGORITHM

The major functions of automation can be realized by implementing algorithms in various blocks of grid automation components. These algorithms executing on an embedded platform, takes measured data as input, executes complex logic to analyze various conditions and control operations as shown in Figure 3. As automation research engineers, we realize that the counterweight to implement technology on automation is the high cost which includes design, installation, equipment and maintenance. Many power system networks have adapted available technology for various benefits, apart from these hardware and software technology requirements for building automation, the other major consideration in developing automation network is ongoing need for human operators to continue in maintaining and extending the automation network into the future at once the benefits of automations are realized by the operations side of power system or grid, there will be a demand to automate the entire existing system and any new devices added in the future, to be a smart grid.

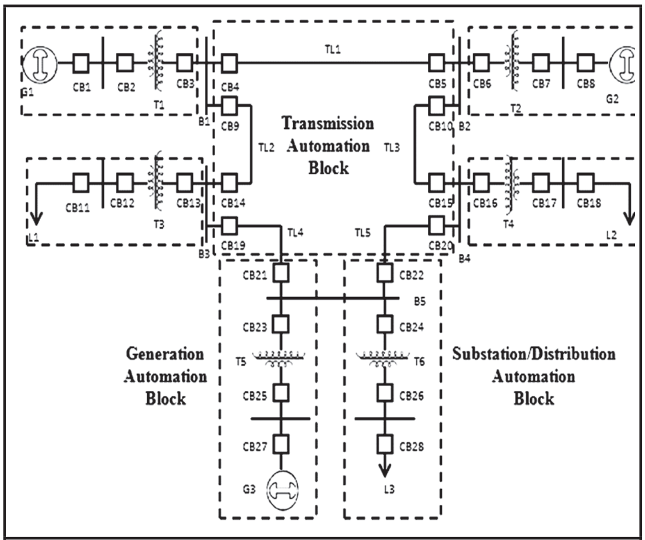

FIG. 4 GRID AUTOMATION BLOCKS

To accomplish this deciding the communications protocol and interoperability between various nodes plays a vital role. Hence there is a need of standardized automation systems which can communicate and operate on a standard protocol and design framework.Grid automation across thesystem can be visualized as combination of generation, transmission, substation and distribution automation blocks as shown in Figure 4.

4.0 SMART GRID AUTOMATION ANALYSIS

In this section we shall broadly see the various recent trends in Power System Automation for each of the individual automation blocks that helps in meeting some of the smart gird objectives mentioned in Section 2, in generation/ transmission/ distribution sectors. Various future opportunities are discussed in further sections. In all further sections '⇔' indicates data & information or energy flow in both directions.

A. The major trends in generation automation are :

Control Systems *:* The automation controller in the Instrumentation & Control panel of power plant is a major component [4]. Since the generation and demand should match for better operation of the grid and since it is not possible to store excess power or generate instantly more power, these controllers played a key role in automation for a fail-safe mode of operation in which the following functions are controlled automatically; Stress on turbine during startup & shutdown, Synchronization with grid, Ability to control the loading of turbine and generator, Frequency limit violation check to avoid penalties, managing the load internal to plant apart from external load, Prevention of overloading of turbine & compressor unit, Protection and control against faults and possible failure modes. Embedded system platform forms heart of control systems.

Distributed Control Automation *:* Use of advanced communication technologies in a highly integrated control environment has drastically improved the performance of control systems. Micro-controllers played a key role in implementing distributed control system with the ability to connect to external networks, possible to have supervisory control of plant state, robust fiber-optic-based network to communicate with local controllers, modular system design for automation [5]. The distributed platform is realized by incorporating various logical control nodes (LCN) as shown in Figure 5 which computes their own algorithms without the need of any central node for functioning, offering wide variety of flexibility in plant control and automation. Thesealgorithms are realized by a set of equations governing the operation of a specific logical node.

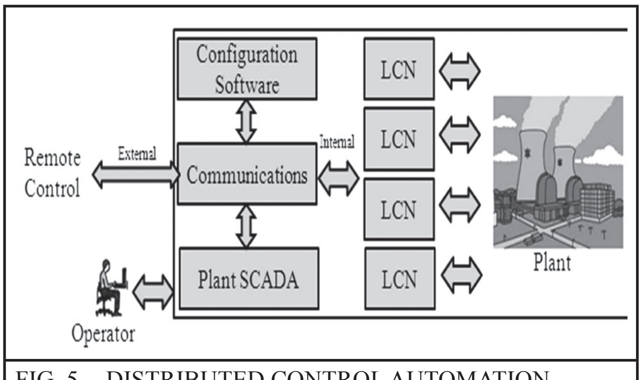

FIG. 5 DISTRIBUTED CONTROL AUTOMATION

Use of adjacent substation technology : After its successful implementation and operation in substation automation, IEC 61850 standards have been attracted by generation automation engineers to realize protection, control and automation functions in a power plant. IEC 61850 GOOSE messaging and necessary logic programming on protective relay IEDs has resulted in higher performance with more data to monitor and troubleshoot the issues in real time. Such applications of configurable GOOSE messages are, to reserve interlocking or reverse blocking, breaker failure protection, high voltage direct transfer trip and load shed/transfer, while the traditional advantages of GOOSE such as reducing the amount of copper wire and relays necessary for protection is well acknowledged. Also, custom defined object oriented models of IEC 61850 helped in realizing various logical node operationswithin the power plant [6]. Apart from GOOSE, the other major advantage came with the usage of enhanced security controls such as select before operation capability, wherein it allows for selection of the control object before executing control commands to breakers and switches, generator, turbine and transformer control parameters to avoid multiple commands.

Foundation Field Bus Automation: Foundation field buses being the digital serial two-way communication system for plant or factory automation after successful implementation in the process industries has attracted power plant engineers to use it. Its targeted applications based on regulatory control offer discrete control & automation [7]. There are two different implementations of the foundation field bus using different physical media and communication speeds [8]. H1 working at 31.25KB/Sec connects to field devices and provides communication and power over twisted pair wiring. HSE works at 100MB/Sec and typically connects IO subsystems, hosts, gateways and field devices using Ethernet cables. This is similar to station bus and process bus concepts in substation automation based on IEC 61850, however field bus specifically targets power plant applications.

Advanced Web based technologies : Web based technologies were traditionally not used in the automation environment earlier because real-time monitoring and reliability requirements are quite high which sets higher performance standards compared to a common web page. However with the advent of advanced software technologies, it seems that web based control mechanisms are well suitable for automation environments like SCADA to certain extent like monitoring functionality but the need to provide direct access to automation system parameters will set limitations [9]. These advanced software based HMI's helps in viewing the exact field conditions by means of animations, 3D visualization and different coloring schemes for differentiating different types of faults for the critical plant equipments.

B. The major trends in transmission automation are :

The Transmission system has been a monopoly in its operation for a quite long time and has robust algorithms built in early 80's and 90's which made it fail-safe in operation and less prone to faults. Though the major amount of trend in automation is seen as generation and substation/distribution ends today, these are some of the recent trends in transmission automation side,

Wide-Area Measurement Systems:

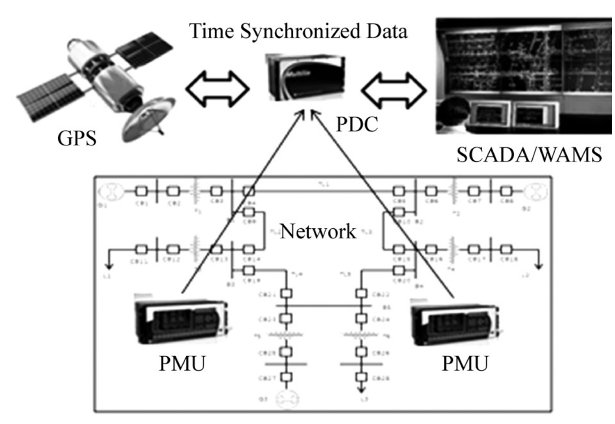

FIG. 6 WAMS BASED TECHNOLOGY

As the power systems becoming large and exhibiting increasingly complex nature, there is a need for advanced measurement technology, tools, data analytics and operational infrastructure that facilitates the better automation, control and management of complex power system. Such system is called as Wide Area measurement System (WAMS) which uses advanced satellite based time synchronization technology for complete monitoring, protection and control of the power system [10]. WAMS is a standalone infrastructure that complements the grid conventional SCADA uses PMU's and PDC's integration as shown in Figure 6 and increases the situational awareness of operator for safe and reliable grid operation.

Next Generation EMS and SCADA : Though Energy Management Systems and SCADA were available predominantly from quiet long time performing operations like state estimation, optimal power flow, security analysis, contingency analysis, stability analysis etc., the present trend [11] in automation in this area are automatically scheduling inter-area power exchange, computing online power transactions, handling deregulated and restructured power system operations, allocating costs to various generating participants, monitoring system security against possible physical and cyber attacks, wide area stability analysis, state estimation based on WAMS, optimal bus load shedding based on critical bus synchronism lost etc.

Advanced Flexible AC Transmission Systems: The power electronic based systems offering control of AC transmission parameters for enhancing stability and increasing power transfer capability were traditionally based on series and shunt compensation devices [12]. With the evolution of WAMS, FACTS has now become much more robust in control due to the accurate and timely measurement of reference parameters. Communication has been added to these FACTS devices which made it interoperable with remote control operations based on WAMS. The present trend in automation is to automatically control transient stability of the line, damping of the system, voltage stability, sub-synchronous resonance, short-circuit current levels, integration of wind power generation to the grid and terminal performance of HVDC converter using the FACTS based device.

Power System Cyber Security : Today's Energy Management Systems and SCADA systems are predominantly based on Local Area Network (LAN) and Wide Area Network (WAN) communications. Multivendor protection, control and monitoring IEDs integrated with various control centers or gateways at substation carry information to a central control center [13]. Hence methods for information security to assure privacy of data and information, integrity of data and commands from control centers and authentication of the source of receiving data and commands play a critical role. In the present trend, automated security systems that complement the existing SCADA system, performs the intruder detection for possible physical & cyber attacks based on a set of protocols and executes data integrity based algorithms using the knowledge of power system components, control actions to differentiate authentic and false trip commands due to malware [14]. Cyber Security indeed is required for all automation blocks.

C. The major trends in substation / distribution automation are:

The whole feel of automation in today's power system is felt by substation and distribution automations which are widely deployed and in use. The realization of full benefit and extended functions of individual automation systems are still under evaluation. Since these automation systems add significant cost to the existing grid, they need to be used to the greater extent possible. Some of the recent trends in substation and distribution automation are illustrated below.

Micro - controllers and communication networks: Earlier when protection devices were based on electro-mechanical technology with hard-wired communication they offered some limitations in terms of speed and operation. They were slowly replaced with micro-controller based devices which increased the speed of operation. With the advent of advanced micro-controllers today the diversification and complexity of functions required by automation becomes a strong trend of evolution [15]. In present trend, addition of powerful communication networks based topologies offering high-speed communications to these micro-controllers have made Intelligent Electronic Devices (IEDs) more robust to handle multiple faults, analyze more data and perform automation functions in a much more efficient and reliable manner as required by the complex power system. A single IED can monitor entire bay in a substation.

IEC 61850 based Substation Automation System (SAS) :

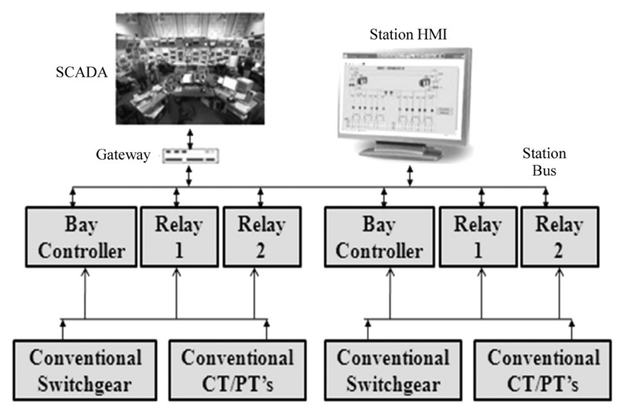

FIG. 7 IEC61850 BASED SAS

IEC 61850 standard for substation automation has totally revolutionized the power delivery industry since its introduction in 2005 time frame [2, 16]. The major breakthrough happened with the realization of "Interoperability" between multi-vendor IEDs. 61850 also offer easier configuration, standardized logical nodes and functions for every equipment, high-speed Ethernet communications on station bus, and peer-peer communications called GOOSE, enhanced security controls, predefined XML file formats etc. At present such system as shown in Figure 7 performs monitoring, control, recording and protection functions in a substation.

Substation to Feeder Automation : Initially IEC 61850 Substation automation was more focused on operations and control within a substation, later the same has been extended to feeder automation by a virtual extension of SAS having built-in intelligence in IED along with high speed communications and controls. Feeder automation can be realized in a centralized or decentralized approach based on number of feeders covered [2, 17]. Decentralized approach offers more flexibility however centralized approach provides wide-area automation at the trade of high implementation cost. At present, such systemsprovide automation functionalities such as automated fault detection, isolation and service restoration, phase and load balancing of feeders and transformers. The major advantage of feeder automation is reduction of losses and power interruption time, leading to better power quality and reliability. Automatic fault location identification quickly helps in restoring power to Un-affected zones of network early.

Software based Intelligence in SAS : The automation and control of the current electric power systems based on the SCADA model though provides adequate reliability and speed of operation it does not offer flexibility in terms of open access to information. Due to the intrinsic distributed nature of power systems, multi-agents based technology can provide greater autonomy for each component in power system [18]. In present trend, agents play key and distinct roles in monitoring and control, communication by means of messages, information retrieval through mobile based agents travelling over the network and interaction between agents for specific tasks. However this merely did not provide any major advantage over IEC 61850 based SAS and has not seen any practical implementation or advantage so far.

IEC 61850 Process bus Automation : The substation secondary equipment such as sensors, transducers etc. measures various analog parameters like voltage, current, temperature and transfers to main relay using hard-wired cables. When it comes to replacement and maintenance of substation secondary equipments, it may impact the overall substation availability because of complex wiring and relay obsolescence [2,19]. To overcome this problem IEC 61850 has introduced process bus which is similar to field bus in generation plant, where in a standardized Ethernet bus is used to provide interfaces to primary equipment. A merging unit (MU) collects all the data from field sensors in a synchronized manner, digitizes the signals and transfers the sample values automatically on high speed Ethernet or process bus (1Gbps) to the subscribed primary equipments. This helps in reducing maintenance cost and time for re-configurations. However the process bus requires high accuracy of measurements with respect to time, which was later added by IEEE 1588 precision time protocol (PTP) over SNTP [20] which made even 20ms time period wave analysis possible today and multiple IEDs to look at same zone using these accurate time measurements increasing reliability of protection [21].

Distribution Automation (DA) : While there is an overlap between the substation and distribution automation, based on IEC 61850 the main aims of the distribution automation system shown in Figure 8 being Supervisory Control and Data Acquisition (SCADA), Volt & Var Control (VVC), Fault Location (FL), Feeder Reconfiguration (FR) (Self Healing), FLISR (Fault Location, Isolation, and Service Restoration), which is a hybrid of FL and FR [2, 22]. These automation applications were tried to realize from various methods like agent technology [23], genetic algorithm [24] etc. however IEC 61850 extended distribution automation gives more advantage and closer to practical implementation. The present trend is continuing towards multi-criteria analysis for feeder switching, reconfiguration, balancing etc. based on software based computational algorithms.

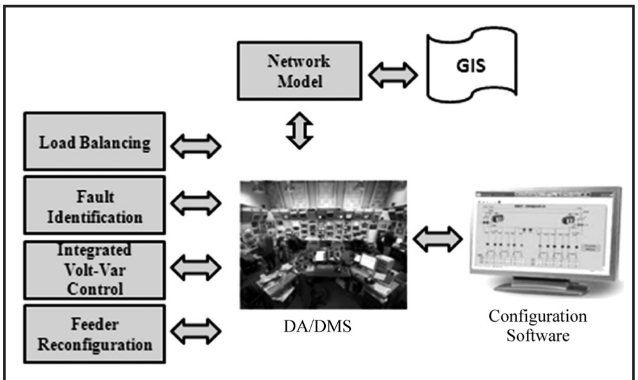

FIG. 8 DISTRIBUTION AUTOMATION SYSTEM

Distribution Automation communications : It is far possible to realize automation without communication which offers remote monitoring and control of the distribution system. Though there are only one TCP based protocol being used for communications from generation to substation automation, however distribution automation is being realized on a wide variety of communication types like PLC (IEC 61334), Ethernet, RS 485, wireless, 3G, CDMA, WI-Max, Zigbee, GPRS, GSM [2, 25-27] etc. the reason being distribution closer to end users who use these communications often in day-to-day life. The present trend is to optimize and enhance the distribution automation functionality with wide variety of communications possible based on requirement.

Advanced Metering Infrastructure (AMI) : The AMI systems as shown in Figure 9, usually collect data from various smart meters in the field in an automated manner using DLMS/COSEM (IEC 62056) standard specification and transfer it to a central location called Meter Data Management System (MDMS). The AMI network offers low-bandwidth two-way communication links between meters and back office [28]. The major trend in AMI is premised automation of a customer by forming, Home Area Network (HAN), Neighborhood Area Network (NAN) using Zigbee, PLC and GPRS wireless based communications to control smart appliances and smart meters. These networks also help utility to perform demand response. Such systems are widely being deployed now though cost of investment needs to be yet fully justified as explained in distribution automation challenges in further sections.

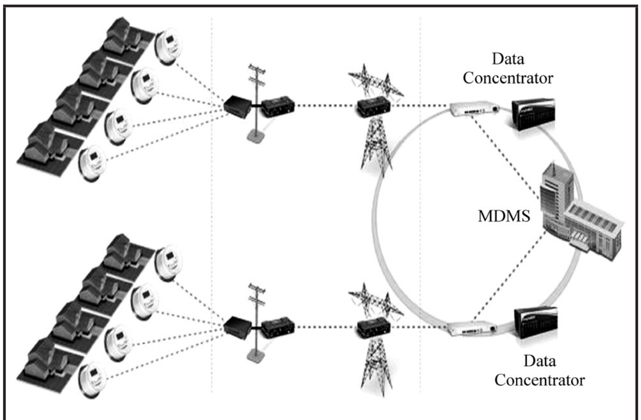

FIG. 9 AMI SYSTEM

Micro-grid Automation : With the evolution of a variety of energy resources like solar, wind etc. apart from regularly used natural resources for power generation led to the formation of Micro-Grids as shown in Figure 10, which can operate in synchronization with grid or in an isolated mode during an outage of the grid, supplying power to local load in a distributed manner to fill the supply and demand gap during peak loading conditions on the grid. When the micro-grid is operating in islanding mode and when the demand increases beyond its supply, it may lead to grid collapse [29]. Hence the present trend is to automatically control the demand on a micro-grid to maintain stability under various loading conditions, especially during islanding mode, using communication based load control technologies.

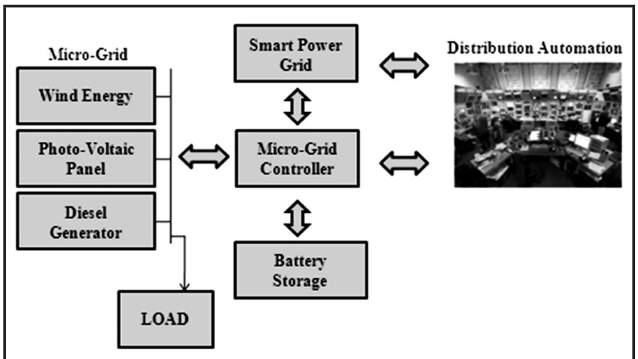

FIG. 10 MICRO-GRID SYSTEM

5.0 CONCLUSION

Various emerging trends in power system or grid automation have been analyzed from generation to distribution. Latest technology trends and solutions for automation in the last few years have been presented in a crisp, consolidated and rigid manner. It is clearly visible that power system is a complex network and automation plays a key role in protection, monitoring, control and operation of various components of the grid from generation to distribution offering a higher degree of reliability, quality and efficiency leading towards smart grid. Also automation significantly reduces downtime and increases the availability of power supply and equipments from generation to distribution, which is one of the major goals & objectives of smart grid in the 21st century. Hence the power system or grid automation will definitely lead to smart grid objectives fulfillment to the major extent possible and smart grid automation will further evolve with new challenges and solutions in forthcoming years.

6.0 FUTURE OPPORTUNITIES

The first major challenge in any automation system today, from generation to distribution is to optimize cost of investing in automation technologies, by realizing larger extent of benefits from grid automation functions than existing in today's scenario. The optimal cost/benefit ratio should be identified and justified as shown Figure 11 above, wherein the units for the benefit varies based on automation function & type ex: dollars saved from no power interruption, reduced fault clearance time in hours etc.

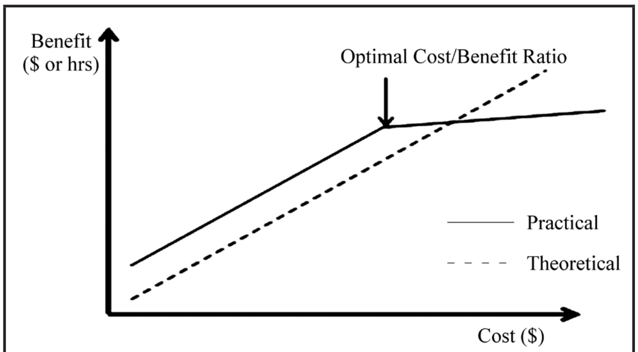

FIG. 11 AUTOMATION COST/BENEFIT ANALYSIS

Future opportunities & challenges in, Generation Automation : Asset Management and Optimization for power plant assets based on real-time condition based automatic monitoring techniques, Introducing human factors based intelligence in automation, Embedding expert knowledge in automation software, Advanced visualization of equipment faults using automatic data handling techniques, Remote diagnostics for condition based monitoring & early prediction of faults using advanced data analytics, Big data handling in automation logic, Extension of field bus automation across power plant, and Integration with transmission automation system in a deregulated & restructured power system environment.

Transmission Automation : Advanced optimization and automatic data analysis techniques based on wide area measurements (PMU/PDC), FACTS for better stability & control with standardization, Remote diagnostics for early detection & prediction of faults and outages, advanced automatic contingency analysis and mitigation of generator/line failures using WAMS, Big data handling in automation logic, Integration with Transmission & Substation automation in a deregulated and restructured environment, Cyber Security & Integrity based algorithms in EMS/SCADA/WAMS with automatic self healing capabilities against physical or cyber attacks.

Substation Automation : Incremental and substantial additions to IEC 61850 standard based automation technology further improving reliability, availability and accuracy. Cyber-security in substation LAN network, automatic data analysis for asset management and condition based monitoring of substation transformers, cables, switchgears etc.

Distribution Automation : Wide extension of its capabilities beyond feeder automation such as advanced systems logic & standardization, modeling of automation scenarios, Integrating & operating distributed energy resources with grid more effectively in an automated manner, advanced Micro-Grid control and self-healing islanding operations, wireless communications for monitoring & control till the edge of the distribution network adding intelligence at the edge of the network, integrated load and phase balancing applications, advanced Demand Response based on AMI, Feeder reconfiguration including AMI data, Data Analytics for early prediction of faults, handling Deregulation & Restructuring of the distribution sector effectively, Improving Reliability & Efficiency of distribution grid to a large extent, Intersection of DA and AMI systems to realize new solutions & benefits for smart distribution grid, Use of advanced communication & computer network based algorithms integrated with distribution automation algorithms etc.

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