Advanced Technologies Implementation Framework for a Smart Grid

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Abstract—**Smart Grid is not a single technology or a concept; rather a vision of a perfect blend of advanced technologies and applications. The key technologies and applications are grouped into integrated communications, sensing and measurement, advanced components, advanced control methods, and improved interfaces and decision support; each of them playing an active role in determining the behavior of the grid. The deployment of more and more of these technologies and applications has a great potential for driving innovative ways of producing, consuming, and controlling electricity, yielding benefits to utilities, consumers and the society. This could be implementation of 'smart' meters, 'smart' sensors, advanced communications and intelligent management & control, which when interconnected provides new opportunities to improve efficiency and effectiveness of the system. But the huge implementation of diverse technologies and applications along with its associated infrastructure has thrown up challenges in terms of efficient implementation and management of systems. This paper therefore brings out the critical need of a framework to integrate these technologies and applications, and proposes an architecture that can classify these diverse technologies and integrate them in a single platform for efficient management of the systems and its associated performance. It also addresses the basic requirement of scalability, flexibility, security, consumer privacy, integration and interoperability.**

Index Terms—**Advanced technologies, smart meters, sensors, intelligent electronic devices, management system, FCAPS.**

I. Introduction

Advanced technologies are those components of technology that are still immature, but have the promise to substantially meliorate the future industry to deliver value. They are disruptive and have the potential to significantly impact the society, to the extent of transforming and redefining our daily lives. One of the fundamental transformations these technologies bring to the society is in building robust, resilient and sustainable critical infrastructures for tomorrow. The newly emerging modern electrical grid is one such, which is achieved using a wide range of advanced technologies put into operation.

This emerging grid promises to take advantage of the advanced technologies across the power delivery system to monitor, manage and address the growing needs of customers. While there is a significant progress in implementing smart grids, the initial focus has been limited to the basic applications like advanced metering and meter data management. However with the advanced technologies paving the way, there is a huge focus to go beyond the basic systems, and build a bigger and smarter power delivery system. This involves a huge implementation of diverse technologies integrated into a common infrastructure, enabling unique services and applications. Therefore a major challenge is to build a single central management system, on a mix diverse technologies and systems, most of which cannot understand each other today. A number of bodies like the NIST (*National Institute of Standards and Technology*) and the European Standards Organizations (*ETSI, CEN and CENELEC*) are working on priority, to address these concerns. However the right management system is yet to be defined, and calls for innovative frameworks and architectures.

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II. The Smart Grid

A. Definition of Smart Grid

NIST in its smart grid Conceptual Reference Model defines smart grid, as "*a complex interoperable system of systems for which a common understanding of its major building blocks and how they interrelate must be broadly shared*"[1]. In real time smart grid allows multiple applications to interact over a shared, interoperable network, which allow utilities to optimize and regulate demand and supply. And the underlying communication-network facilitates real-time, two-way communications that enables interaction between each component..

B. NIST Smart Grid Architecture

The conceptual reference model of NIST has divided the smart grid into seven domains: bulk generation, transmission, distribution, markets, operations, service provider and customer (Fig. 1). This model consolidates the grid components to the different domains, determine the mode of interfacing between these domains for intelligent information-exchange and identify the details of interfaces. Any system or device that participates in smart grid functionality is termed as an *Actor*. The actor in one domain which interfaces with another actor in another domain is called a *Gateway Actor*. An *information* establishes a logical communication path between these actors (with in or across domains) using a variety of communication technologies.

The challenge however is the variety in interfaces and protocols required to exchange information between each of these actors and domains. The initial release from NIST identified 75 existing standards, specifications, or guidelines that will be immediately applicable to the ongoing transformation of the smart grid and identified 15 high-priority gaps for which new standards are needed (34 relevant standards and additional 62 standards for further review in Release 2.0) [1].

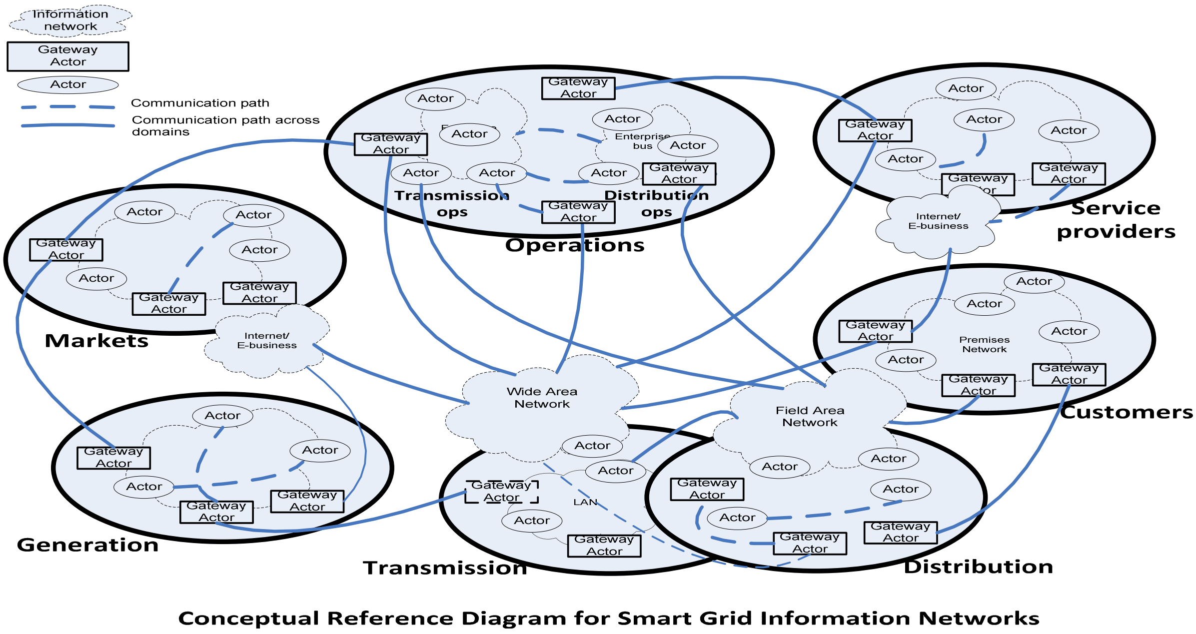

Fig. 1. Smart grid conceptual reference diagram

C. *The Convergence of Advanced Technologies*

A careful study of the transformation in the modern grid can be rightly described by a single term, '*convergence*'. Smart grid is not a single technology or a method or a tool, but rather a perfect convergence of existing and advanced technologies, in building the power system of the future. It is a mix of a wide range of technologies, design concepts, operating practices and business models. When properly implemented, these technologies promise to improve the reliability, efficiency, flexibility, security, cost-effectiveness and environmental impact of the existing power system. In real time, smart grid allows multiple applications to interact over a shared, interconnected, interoperable network, which allow utilities to optimize and regulate demand and supply. It is therefore not a single thing or one time implementation; instead a generic term which describes the vision for the next-generation networks that offer improved efficiencies in distribution of power in the future.

The U.S. Department of Energy Office of Electricity Delivery and Energy Reliability defines smart grid by seven principal characteristics as below [2].

1) customer participation
2) integration of all generation and storage options
3) new markets and operations
4) power quality for the 21st Century
5) asset optimization and operational efficiency
6) self-healing from disturbances, and
7) resiliency against attacks and disasters

According to OE, these functionalities will lead to developing a self-healing electric grid with greatly improved reliability at the same time fully integrating demand response (DR), distributed energy resources (DER) and plug-in electric vehicles (PEVs) as grid resources to improve electric system efficiency. To achieve these principal characteristics, it is critical to pursue critical technological advancements, and globally a wide range of technology components developed and implemented. These advanced technology components can be broadly grouped into five key applications as in Fig. 2.

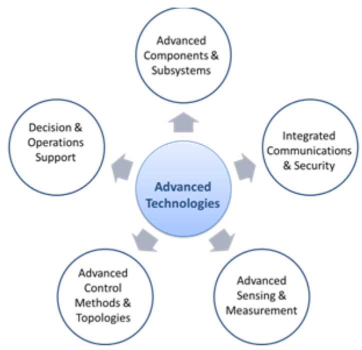

Fig. 2. Smart grid advanced technologies

1) *Advanced Components and Subsystems*

Advanced components play an important role in tuning the behavior of the grid. These components and subsystems are based on latest technology advancements in power electronics, materials, superconductivity, energy storage, robotics, sensors, intelligent devices and controls. They therefore support advanced sensing, integrated communications, real-time diagnostics, actuation, and intelligent controls. One of the greatest factors is the '*in-built intelligence*' and therefore the capabilities of autonomously learning and adapting to the environment, which is termed as '*self-healing*'. A barrier to the development and the implementation of advanced components is the huge cost involved in developing them.

2) *Integrated Communications and Security*

These are the high-speed, fully integrated, two way communication technologies which make the future grid an interactive, dynamic infrastructure for real-time information transmission and power exchange, allowing the users to interact with the different intelligent interconnected devices. Integrated communications and the seamless interaction between the components in the grid is the fundamental component for optimal control of the smart grid. Due to its dependency on data for automation, protection, and control, the future grid cannot succeed without an integrated communications infrastructure. A big dependency is therefore on the evolving nature of standards which must be seriously addressed and encouraged. Although communication and security technologies are very rapidly developed, the universal deployment will be seriously affected unless the standard development is accelerated.

3) Advanced Sensing and Measurement

Sensing and Measurement systems are the eyes and ears of the smart grid. Today a great transformation is happening in sensing and measurement technologies because without it, operators, customers, and automated systems are blind and cannot operate efficiently. At the same time, data quality is a critical issue in utilities today. Every activity in a utility involves data; however, more data does not necessarily mean more information. Intelligent information therefore becomes the foundation for any strategic, tactical, and operational decisions. Advanced Sensing and Measurement technologies therefore enhance power system measurements and transform the data into better information and enhance different aspects of power system management. In the future, advanced meters and sensors, will enable more complex measurements and will also facilitate direct interaction between the utility and the consumer.

4) Advanced Control Methods and Topologies

All the technologies described above require advanced control methods to manage their operations. These are advanced devices and algorithms that will use analytics to diagnose, evaluate and predict different conditions in the future grid and autonomously take corrective actions to mitigate, eliminate and prevent outages and grid disturbances. The advanced control method is a key for a safe, secure and reliable grid. Most grid controls today are centralized and involve human interaction. As the smart grid evolves to one with multiple distributed renewable generation, storage, and load management, more complex automated control systems will be necessary to maintain optimum operation of the grid. The control algorithms will be strongly influenced by the smart grid topology (centralized vs. distributed control). Today's grid hardly has any smart sensors and control devices that need to be deployed to measure the relevant data to provide intelligent control mechanisms to better manage the electric system.

5) Decision and Operations Support

The modern grid will require intelligent use of multiple tools and applications that provide grid operators and managers an enterprise view and enable them in making decisions quickly. Improved interfaces and decision support or IIDS, are essential technologies that will enable more accurate and timely decision making across the grid operations. Sensors, advanced components, and integrated communications and controls contribute to decision and operations support. IIDS technologies will fundamentally convert complex power-system data into meaningful information that can be understood by operators with limited effort. Intelligent dashboards (iDashboards), animation, virtual reality, color coding and other data display techniques will prevent data-overload or bad-data and help operators monitor, detect, analyze, understand, decide and act on issues and concerns in the grid. In many situations, the time available to make decisions is shortened to few minutes, sometimes even seconds and great is the value of quick and timely decisions. Modern grid will therefore require the wide, seamless, of real-time use applications and tools that would enable grid operators and managers to understand the behavior of the grid and make quick and timely decisions, which is very a critical aspect in achieving the objectives.

III. Advanced Technologies Management System

Utilities today are trying to manage their operations using multiple proprietary vendor management systems or home-grown legacy systems and have failed miserably due to lack of standard architecture and other challenges of heterogeneous, non-interoperable and complex systems. This has hampered them from exchanging real-time information, and working together on a wide scale. In fact for these reasons, the worldwide smart grid adoption has been halting and in many places is falling apart, and the progress varying between different geographies.

This paper therefore brings out the critical need of a *centralized management system*, using a multilayered framework that segregates diverse technologies and applications into different layers and integrates them into one single management system. This coalescence of advanced technology components based on a globally accepted and industry proven model, will provide a better platform to manage the complex smart grid infrastructure. The multilayered framework helps in accurately modeling the behavior and performance of all the components contributing to the power delivery system at different levels of grid operations from generation to transmission and distribution. It also helps to better understand the impacts of frequent changes in terms of renewable resources, demand response, as well as economic and business environment, and technology advancements. This futuristic system therefore becomes a vital component, in achieving the vision of having and intelligent platform that supports plug-and-play of diverse and advanced technologies, at the same time addressing the basic requirements of scalability, flexibility, security, consumer privacy, integration and interoperability.

A. Framework Description

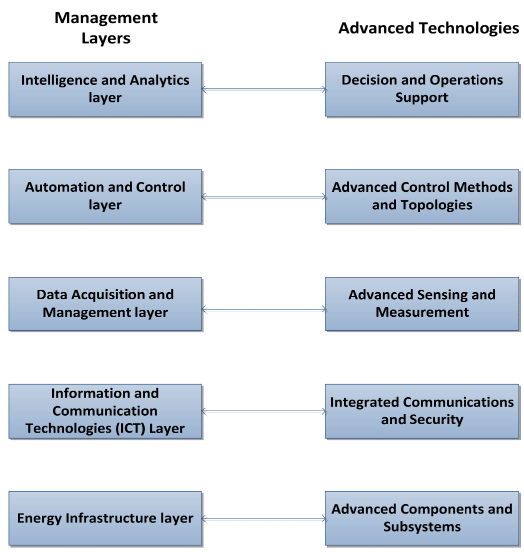

Fig. 3. Management layers and the advanced technologies

The basic components that make the smart grid said can be grouped in two different domains: the Energy Infrastructure (generation, transmission & distribution), the Information and Communication Technologies (ICT) Infrastructure. The success of a smart grid implementation is mainly dependent on this ICT infrastructure underlying the smart grid systems, that can collect and communicate energy data in real-time. And the DNA (building block) of the smart grid is the seamless interconnection and integration between each of them.

On an architectural perspective, the proposed management system is built as a multilayered framework which integrates the different management layers into one single system. The elements of the smart distribution system are categorized into different layers (Fig. 3), based on their key functionalities in implementing a smart power system [3].

1) Energy Infrastructure layer
2) ICT Infrastructure layer
3) Data Acquisition & Management layer
4) Automation & Control layer and
5) Intelligence & Analytics layer

Another uniqueness of this framework is that it perfectly aligns the advanced technology components with the management layers (Fig. 4). This therefore provides great value in terms of understanding the end-to-end interoperability, and therefore efficiently managing the smart grid system.

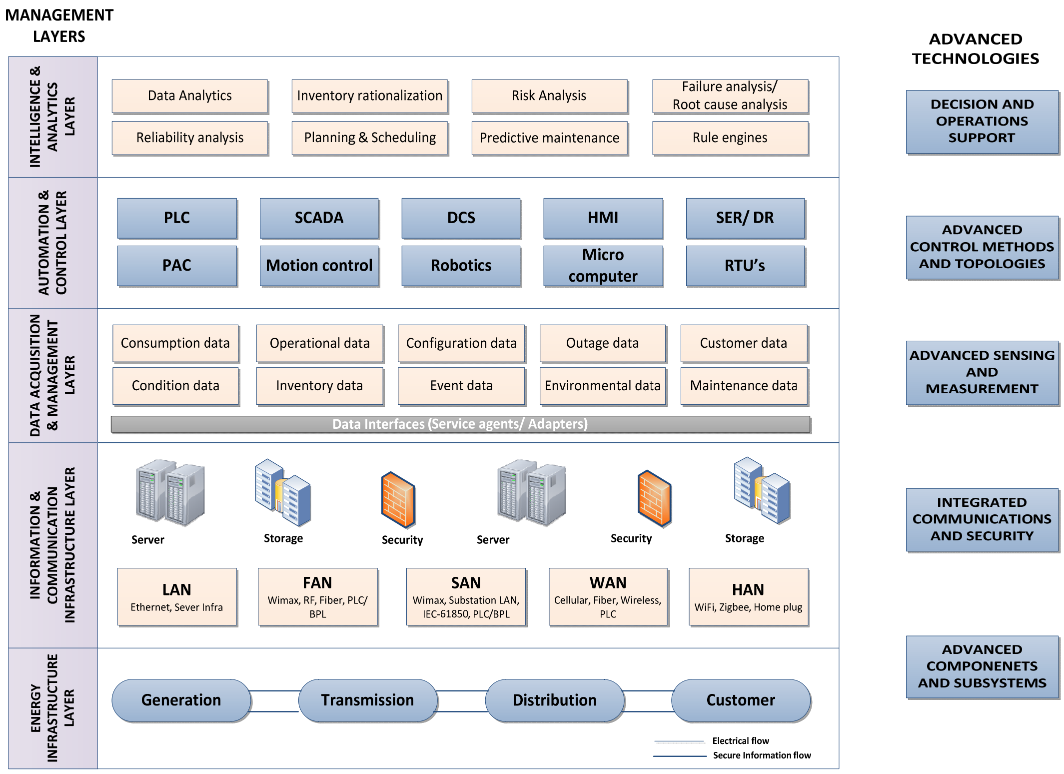

Fig. 4. A layered view of the management layers

This management System is built on the industry accepted and proven model of FCAPS, as introduced in the Telecommunications Management Network (TMN) [4]. In FCAPS the general management functionality is divided into five key areas namely, Fault, Configuration, Accounting, Performance and Security, and describes the five different types of information dealt by management systems. This model is being used in communications industry for decades in building and managing their network elements, which is equally complex and widespread.

1) Energy Infrastructure Layer

The energy infrastructure is the foundation for the basic energy transfer in a grid. For analysis, the physical infrastructure can be divided into three parts; generation, transmission, and distribution. The physical layer therefore includes all electrical infrastructure components for generation, transmission, storage, distribution and consumption of electrical energy.

Generation is the first process in delivery of electricity to the customers. It is connected to the transmission domain which supports bulk transfer of electrical energy from generation to distribution, through multiple substations. The transmission network is normally controlled through a SCADA system together with its communication network and control devices. Customer domain is where the end user operates and has sub-domains such as home, commercial building, and industrial. Each of these domains contain different devices such as generators, turbines, transformers, protection relays, remote terminal units, capacitor banks, fault recorders, and programmable logic controllers which aid in delivering of electricity to customers

Advanced components & Subsystems play active role in tuning the electrical behavior of the grid. Smart grid today uses advanced components with pervasive sensing and in-built intelligence, supporting advanced sensing, integrated communications, real-time diagnostics and intelligent controls (Fig. 5). Some of the prominent components and their applications are mentioned below.

1) Key distribution system components such as relays, breakers and transformers augmented with solid-state power electronic devices that provide precise, flexible, and automated control
2) Power electronics distribution transformers that provide voltage regulation, harmonic suppression, and power factor correction.
3) Application of flexible AC transmission systems (FACTS) at the distribution system level to transform the way distribution networks are operated
4) Intelligent loads and active sources that allow loads and active sources (such as PV and energy storage) to be controlled either by price signals or system reliability needs
5) Vehicle-to-grid and grid-to-vehicle technologies that enable efficient integration of electric vehicle (EV) charging
6) Energy storage mechanisms and associated controls.

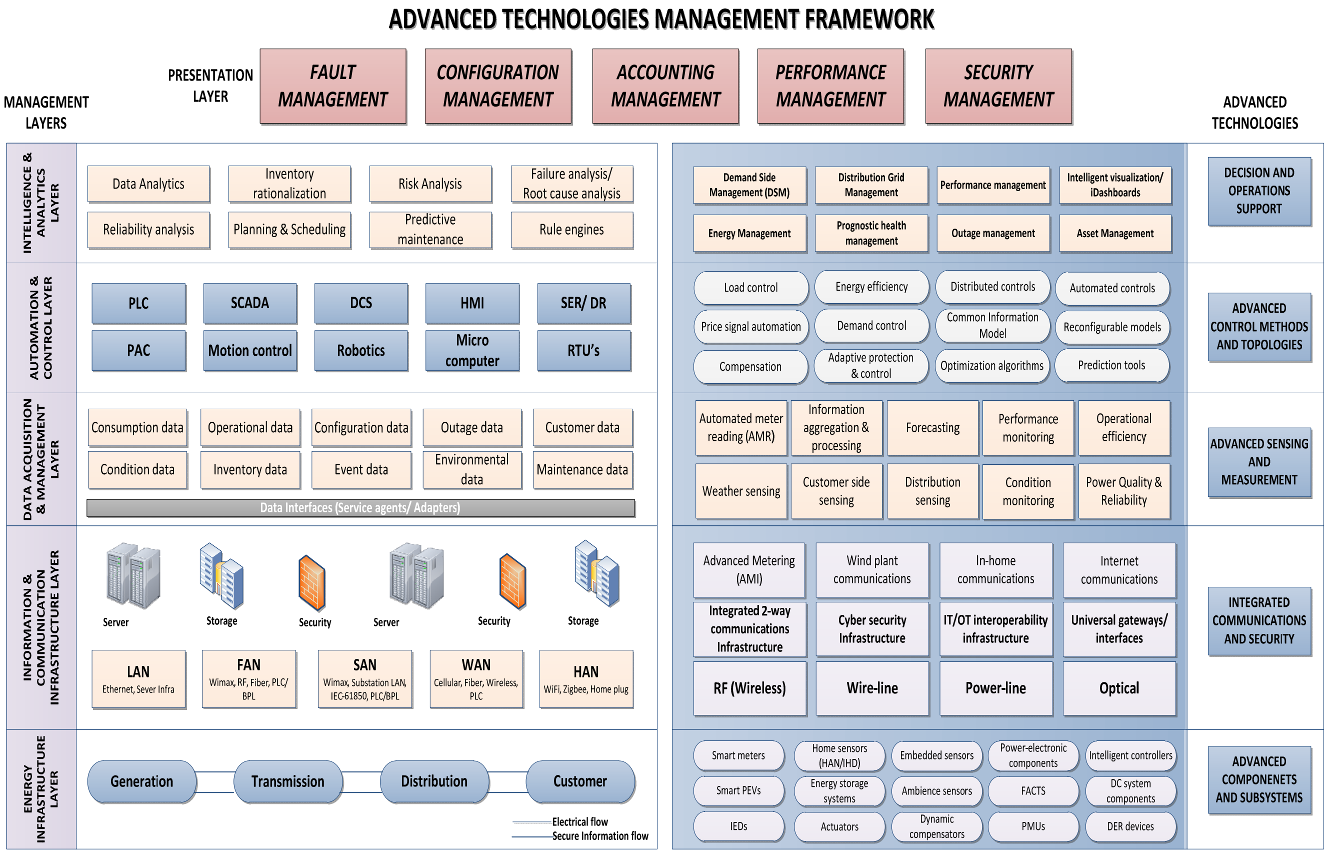

Fig. 5. Advanced technologies management framework for a Smart Grid

2) ICT Infrastructure Layer

The increased coordination between each of the systems to realize an effective smart grid operation is enabled through the bi-directional flow of information. This layer therefore groups the communication and IT infrastructure components. The communication infrastructure can be broadly classified into the following segments [5].

1) Home Area Networks (HAN) - referred to as the Premise Area Network or Building Area Network; this includes devices within a single premise (industrial, commercial or home) communicating over one or more networks. They communicate through a home gateway, bridging utility and home networks.
2) Field Area Networks (FAN) -these devices communicate over one or more networks and backhaul WAN's. This network primarily supports the Advanced Metering Infrastructure deployment.
3) Substation Area Networks (SAN) - these devices communicate over one or several networks inside a single electric substation. IEC 61850 is gaining momentum as the prominent protocol used for Substation Automation.
4) Wide Area Networks (WAN) - referred to as 'backhaul' communications and all broadband technologies like PDH, SDH, SONET and WDM make the communication network between the control room and substations. This could use wireless or wire line communication modes over fiber or free space. Power line carrier communication (PLCC) is also used for wide area communication, however has a narrowband.
5) Local Area Networks (LAN) – this refers to a "close" set of devices in communication, in a local configuration, often in a single building or office location.

The IT infrastructure includes datacenter and the security infrastructure which play an important role in collating appropriate information from the underlying network. A good management system should have strong infrastructure for quickly collecting the data and storing it for further data analysis and intelligent decision making. Cyber security is a serious concern when multiple systems are interconnected for seamless data transfer, in a smart grid set up.

Integrated Communications and Security at all scales is the backbone of the smart grid system, which transmits information to where it is needed and when it is needed for optimal control of the smart grid. Different from wireless and power line communications to microwave and optical technologies will be used (Fig. 5). Since each technology offers its own strengths and weaknesses, solutions could include coordinated combinations to optimize both security and features. Cyber security is imperative to widespread acceptance and adoption of a smart grid that is more dependent on information for control purposes. The communications technologies integrate with the with the sensing and measurement components along with control and actuation functions to bring efficiencies to the grid.

3) Data Acquisition & Management Layer

The data acquisition and management layer consolidates the data from the variety of underlying components and subsystems and processes it to usable data. It validates consistency between the data obtained from different sources. This layer is interfaced with the ICT layer through different data interfaces connected in a middleware environment. The interfaces could be industry-standard protocols (wherever available) or tailored or vendor specific plugs to accommodate legacy systems. Data pulled using the different data interfaces can be grouped into usable data namely, consumption, condition, configuration, customer, operation, inventory, outage, environment and maintenance. This makes it simpler for the automation & control layer as well as the intelligence & analytics layer to effectively and efficiently manage the smart grid infrastructure. Technology advances in software and hardware data aggregation and data-set reduction techniques can reduce the information to a meaningful size for further use.

Advanced Sensing and Measurement can be considered as the information receptors in a smart grid environment. Several key technologies are used for real-time and reliable sensing and measurement (Fig. 5). Some of the prominent components and their applications are mentioned below.

1) Ambience sensors that monitor weather conditions, wind velocity, and ambient temperature which would help unpredictable wind and photovoltaic (PV) energy more predictable
2) Smart meters as the key sensing component for Advanced Metering Infrastructure (AMI). Next generation AMI would have functionality and be able to interface with distributed generation and PEVs.
3) Customer-side sensors within HAN and buildings to provide the customer additional information on energy usage and power quality.
4) Ubiquitous high-speed distribution system sensing voltage magnitude, current magnitude, real and reactive power flow direction, and phase angle that can provide the utility or automated control systems the ability to more optimally manage distributed resources
5) Phasor measurement units (PMUs) for accurate measurement of phase angle, to prevent unintentional islanding or facilitate grid synchronization
6) Embedded sensors supports condition monitoring to improve prognostic health management (PHM), which can increase the reliability of the grid

4) Automation & Control Layer

Automation and control refers includes the set of technology components that help in the operation of assets without significant human intervention. The automation and control layer provides a bridge between the data management layer and the intelligence and analytics layer. It includes all the automation and control devices such as supervisory control and data acquisition (SCADA), programmable logic controllers (PLCs), programmable automation controllers (PAC), human machine interface (HMI) systems and the enterprise level solutions like enterprise resource planning (ERP) systems. These applications range from low level systems which are already available to manage their daily operations, to the mature and intelligent systems, forming the foundation for smart grid. Advanced applications with increased functionality and centralized management allow operators and executives to make business decisions from the real-time information from a smart grid. However the challenge is to collate all the information from different systems which are in different formats to a meaningful single-pane view, needed to take necessary action(s) and drive the business needs.

Advanced Control Methods and Topologies are the algorithms and devices that will monitor, diagnose, understand and predict conditions in the grid to determine appropriate corrective actions that can prevent and mitigate outages and power quality disturbances. All of the technologies require advanced control methods to govern their operation and as the complexity of the smart grid increases, more complex automated control systems will be necessary to maintain optimal operation (Fig. 5). Some of the prominent components and their applications are mentioned below

1) Distributed controls for decentralized control approaches like micro-grid topologies, and nonlinear and robust control mechanisms to design of complex automated controls
2) Automated and flexible distribution system, capable of anticipating and responding to disturbances or malicious attacks while continually optimizing its own performance in distribution grid automation.
3) Self-healing features such as the ability to dispatch DER and reconfigure power flow, so that the faulty or damaged equipment is immediately isolated and the grid security is improved
4) Control mixed AC/DC systems to enable highly differentiated quality and reliability service to customers
5) Adaptive protection and control for high-penetration DER and changing network conditions

5) Intelligence & Analytics Layer

The Intelligence and Analytics layer is built with analytical components which intelligently analyses the data retrieved from the underlying layers and help users in quick decision making. The primary function of this layer is to take intelligent decisions and provide intelligent visualization of the complex power-system that can be understood by human operators. It therefore continuously interacts with the relevant data residing at the data management layer. This layer accommodates all the applications performing end-to-end operations and needed to operate a modern grid, such as demand side management (DSM), energy management (EM), outage management (OM), asset management (AM), Prognostic health management (PHM), distribution grid management (DGM) and visualization. Each of these applications may use different components and technologies to perform their functionality.

Decision and Operations Support- all the underlying technology components contribute to decision and operations support (Fig. 5). Some of the prominent components and their applications are mentioned below

1) Information aggregation and processing to process huge amount of data quickly and accurately, to make operating decisions and to take action as required for maintaining reliability
2) Visualization components displaying only the critical information for quick and error-free decision making at times of emergency grid events.
3) Increased information for consumers and make intelligent decisions regarding their energy consumption.
4) Diagnostic, service, and maintenance tools for outage management systems for installing, monitoring, maintaining, repairing, replacing, and disconnecting devices and services in the field.
5) Advanced technologies that provides operations support tools like- demand response, distributed generation, storage resources, voltage control, detection & isolation of faults, failure analysis, root cause analysis, planning & scheduling, reliability analysis, inventory rationalization and asset management

6) Presentation Layer

The management layer is built upon the ISO's globally accepted FCAPS model (Fig. 5). Therefore data specific to FCAPS functionality is collated from the underlying technology components and segregated between F-C-A-P-S using built-in intelligence and analytics [6]. The presentation layer can be viewed as a *Manager of Managers*, which provides the grid operators with an end-to-end single pane view of the heterogeneous grid. This single pane view to a large extent helps in efficiently managing the grid and in making real-time business decisions.

Additional intelligence can be built-in to also analyse the results, draw co-relation between multiple events (in case of a major failure) and narrow down to the single cause of the event. It helps in easy isolation and quick restoration of service(s). This in a big way helps implementing a self-healing grid by configuring back-up routes and restoration paths; a finely orchestrated grid. It is advisable to implement a scalable architecture for the futuristic needs, and to keep pace with the exponentially growing infrastructure.

IV. Conclusion

As utilities move ahead with smart grid implementation initiatives, they are suddenly thrown up to the challenges of managing a huge infrastructure with advanced components and diverse technologies. Utilities are trying to face this by using multiple proprietary vendor management systems or home-grown legacy systems, but have failed miserably due to lack of standard architecture. This paper therefore brings out the critical need of a centralized management system in a multilayered framework that segregates diverse technologies and applications into different layers and integrates them into a single management system. This coalescence of advanced technology components based on a globally accepted and industry proven model, will provide a better platform to manage the complex smart grid infrastructure. Such a futuristic system is a vital component in achieving the vision of supporting plug-and-play of diverse and advanced technologies, at the same time addressing the basic requirements of scalability, flexibility, security, consumer privacy, integration and interoperability.

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