Smart Grid:
The Road Ahead

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1. Introduction

From the time that Thomas Edison commissioned the world's first power system in 1882, the electric power industry has continually moved forward – working to improve the functionality, efficiency, and availability of electricity. Through evolutionary advancements in technology, the electrical power industry has transformed the way we generate, deliver, and consume power today.

As the electric power industry begins the next century, it is on the verge of a revolutionary transformation as it works to develop a Smart Grid to meet the needs of our digital society. Society's expectations and Utility Commission incentives/penalties are driving changes to the industry where secure data is required quickly, on-demand, and in an easy to search way. Customers are demanding higher reliability and greater choice, and are willing to examine and change their energy usage patterns.

To achieve the end-goals stated above, a unified vision of the road to the Smart Grid is needed. Without a unified vision, the issues currently facing the power system will be addressed piecemeal by utilities, government agencies, and related power system organizations. The result of isolated development activities will be a power system that is plagued by islands of separation. Subsequently, the power system of the future may only be realized in limited areas or on a small scale. This article presents a definition of the Smart Grid and examines the road ahead to its development, which is only possible when power system organizations work together to provide a more capable, secure and manageable energy provisioning and delivery system. (IntelliGrid Architecture Report: Volume 1, IntelliGrid User Guidelines and Recommendations, EPRI, Palo Alto, CA and Electricity Innovation Institute, Palo Alto, CA: 2002. 1012160.)

2. The Smart Grid

According to the IntelliGrid Architecture Report cited above, the Electric Power Research Institute (EPRI) defines the Smart Grid as:

- A power system made up of numerous automated transmission and distribution (T&D) systems, all operating in a coordinated, efficient and reliable manner
- A power system that handles emergency conditions with 'self-healing' actions and is responsive to energy-market and utility needs

- A power system that serves millions of customers and has an intelligent communications infrastructure enabling the timely, secure, and adaptable information flow needed to provide power to the evolving digital economy

From this definition, we can conclude that the Smart Grid must be:

- Predictive (operationally and functionally) to preclude emergencies
- Self-healing to correct/bypass predicted/detected problems
- Interactive with consumers and markets
- Optimizable to make the best use of resources
- Distributed in nature with both assets and information
- Transformational to turn data into information
- Secure from threats and hazards

The Smart Grid must provide robust, reliable, and secure communication as well as intelligent electronic devices (IEDs) and algorithms to make the necessary system assessments when needed. To achieve a Smart Grid, the industry must merge copper and steel (electricity generation and delivery infrastructure) with silicon and glass (computation and communication infrastructure). We are currently at the crossroads in the coming of age of both technology areas.

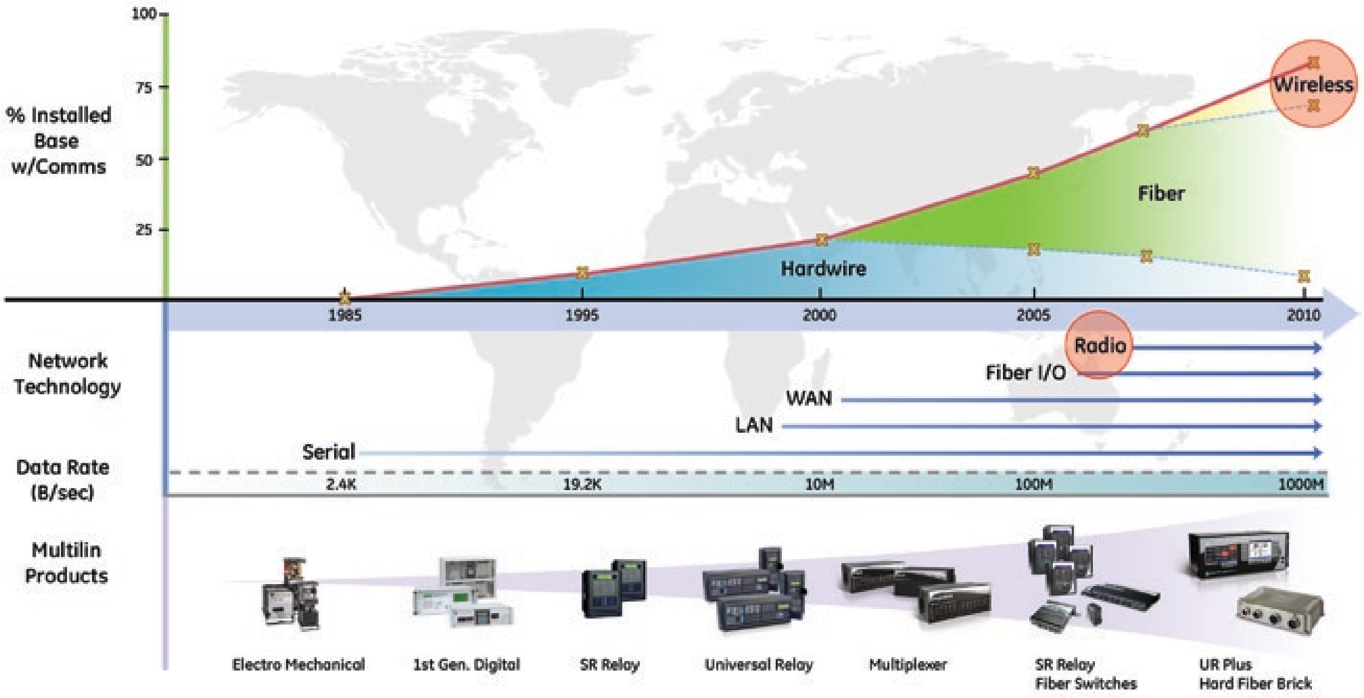

Figure 1.
The Evolution of IED Communications

Over the past 35 years, we have seen communication speeds increase dramatically from 300bps (bits per second) to digital relays that today operate at 100Mbps - an increase of over 300,000 times! (Figure 1) Not only have the communication speeds changed, but the communication protocols have migrated from register-based solutions (e.g. - get the contents of Register 5) to text based data object requests (e.g. - get the Marysville-Kammer Line Voltages) as implemented through the IEC 61850 protocol. In addition, the physical interfaces have transitioned from RS-232 serial over copper to Ethernet over fiber or wireless – both local and wide-area. Interoperability has become a reality and today's devices are self-describing and programmable via a standardized configuration language.

On the device side, the IED and its constituent components have undergone an evolutionary convergence of multiple functions and features into a single device (Figure 2). In the past, protection, control, metering, oscillography, sequence of events (SOE), annunciation, and programmable automation logic were all separate functions. Today's IEDs combine these functions and more into a single platform that provides superior user interfaces allowing visual access to metering, SOE, device diagnostics/solution, and phasor views of data.

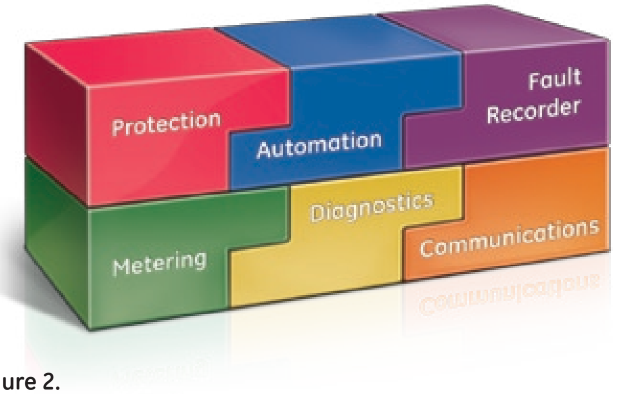

Figure 2.
Convergence of Functionality in Today's IEDs

3. Enterprise Drivers

In migrating towards a Smart Grid, there are three clear enterprise areas that are driving the industry forward: financial performance, customer service, and organizational effectiveness.

3.1 Financial Performance

Financial performance is typically measured in terms of reduced expenditures. In the case of utilities, cost reduction in capital improvement, operations, and maintenance are the primary areas of focus. In the capital improvement arena, advanced communication technologies and global standards, such as IEC 61850, are enabling new architectures and implementations such as Relay-to-Relay communication and Process Bus. These technologies are already demonstrating a reduction in engineering, implementation, and commissioning costs through distributed architecture solutions and soft wiring. Standardized long distance tripping via fiber or wirelessly and analog data communication not only reduce wiring, but also enable new applications such as distributed load shed.

3.2 Customer Service

As described in the introduction, the digital society is demanding higher availability and better quality of electrical energy delivery from utilities. The Smart Grid provides the foundation for addressing these requirements. Detection of incipient problems is facilitated through monitoring and analysis of electrical signatures from the transmission, distribution, and industrial power systems. For example, analysis of electrical signatures from the distribution system can indicate a downed conductor, incipient cable fault, or failed capacitors. On transmission systems, increased communication speeds enable real-time grid control for enhanced stability. In the industrial realm, motor current signature analysis can detect excessive motor vibration, motor turn faults, and broken rotor bars.

In the area of power quality, much of today's electronic equipment demands 100% availability (or at least 99.999%) and preferably clean (minimum harmonic content) power. To meet this demand, the Smart Grid needs to look at new sources of auxiliary power and the means to protect and dispatch power generation in small localized areas. Dynamic filtering of power may be offered as a fee-for-service option. Communication will be key in coordinating this activity throughout the grid.

3.3 Organizational Effectiveness

For an organization to be effective and drive improvement, its people need operational information. Currently, data is gathered through periodic polling of a limited set of measurements and periodic manual inspection of assets.

The Smart Grid view of the substation has changed this paradigm in several ways:

- The IED is monitoring more of the assets in a substation, collecting data, and converting the collected data into information. Timely information about an asset enables optimal use of that asset.
- The IED is able to communicate, on exception, the semantics of the situation. Semantic-based communication provides a standard, unambiguous view of the information and minimizes the documentation and configuration effort.
- The automation aspect provides seamless information aggregation, storage, and dissemination

The overall effect of the Smart Grid in this domain is to improve manpower utilization through automation, and optimized asset utilization through automatic monitoring and operation.

4. Application Domains

As the Smart Grid comes into existence, there are several application domains that promise to drive its development.

4.1 Advanced Metering Infrastructure (AMI) and Smart Home

The first domain, and the area where there is a lot of activity, is advanced metering infrastructure (AMI). AMI represents the next phase of automatic meter reading whereby the meter is responsive to two-way communication, dynamically adjusting for the price of electricity, and interacting with the various loads in the metered facility. The various public utility commissions, who strive to adequately balance the supply and demand aspects of electricity, are driving the implementation of this domain.

The advanced functionality of AMI enables the creation of the Smart Home. The combination of these domains brings to bare functionality such as:

- Real-time pricing/hour ahead emergency pricing /automatic home response
- Direct load control
- Energy usage/optimization display
- Load monitoring/sub-metering
- Remote connect/disconnect
- Outage detection and isolation/customer trouble call management
- Demand profiles
- Security monitoring
- Remote home control
- Remote equipment diagnostics

Home energy optimization will become automatic but the system will also provide user interfaces to foster further energy use optimization (Figure 3).

Figure 3.
Home Energy Dashboard

4.2 Distributed Generation / Microgrids

The second domain driving the Smart Grid's development is Distributed Generation/Microgrids. As the number of Distributed Energy Resources (DER) increases throughout the electronic enterprise, and communication to the various resources becomes more pervasive, the ability to operate segments of the grid as islands or Microgrids becomes reality. The drivers are clear - the desire for high-availability and high-quality power for the digital society. Figure 4 shows a vision of the evolving Microgrid structure.

DER includes not only positive power generation such as solar, wind, and micro-turbines, but also negative power generation through demand response programs, controllable loads, and direct load control. Renewable energy resources are becoming competitive with existing generation resources. Many utility commissions are incentivizing additional renewable generation sources (solar and wind) on the grid. Battery and inverter technology is evolving such that a utility can justify the capital cost of the installation based on the difference in price from buying energy at night at a low price and selling it back during peak daytime rates.

Microgrids do present challenges to the utility from a protection, control, and dispatch perspective. Traditional protection is based on the fact that for a short circuit, significant overcurrents will flow in a direction towards the fault. In a Microgrid environment, a significant portion of the generation will be inverter-based which, through design, is current limited. New protection philosophies will need to be developed to protect these systems.

On the control side, it will be necessary for the Microgrid to be seamlessly islanded and re-synchronized. It may be required that the Microgrid be dispatched as a single load entity. This will mean that a local controller will have to be able to communicate with all of the DERs on the Microgrid, and dispatch both watts and vars, to maintain a constant power flow at the Point of Common Coupling (PCC). The amount of power dispatched will be set either on a contracted value or optimized based on the dynamic price of electricity.

Electric and Plug-in Hybrid Electric Vehicles (PHEVs) provide an additional twist in the operation of the Microgrid because they are mobile. As they connect and disconnect from a Microgrid, the controller will have to be aware of their existence and include their potential effect in the operation of the Microgrid. One of the operational use-cases that evolves from this scenario is the Microgrid controller sending buy/sell messages, that include dynamic pricing information, to the owner of the vehicle.

4.3 Wide Area Measurement and Control

The third major domain area that is rapidly evolving is that of Wide Area Measurement and Control Systems (WAMACS). These systems have the ability to synchronously measure and communicate the instantaneous state of the power system through a measurement known as the Synchrophasor. The ability to dynamically view the state of the power system is similar to being able to view a beating heart. Normal and stressed system states can be assessed in real time and acted upon to affect dynamic control. Today's power system operators take action in the multi-second to multi-minute time frame, but WAMACS can make and execute decisions in the 100 millisecond time frame.

The development of the WAMACS infrastructure entails the installation of measurement and data collection devices in substations, a reliable wide area communication network, and data concentration, visualization, and decision facilities. Work is ongoing in all these areas. As utilities build out their communication infrastructure, they must take notice of the performance requirements dictated by real time synchrophasor communication. Many of the projects will take five or more years to come to fruition.

5. Smart Grid Architecture – Putting the Pieces Together

As the operating scenarios of the above application domains are fleshed out, it soon becomes apparent that there are opportunities and needs for cross-application communication. For example, the WAMACS function detects a system instability and determines that it needs to shed load in the sub-second time frame. It is clear that there needs to be a communication interface between the WAMACS applications and the Smart Home and Microgrid environments. In order to achieve this cross-domain communication, an architecture is needed to define the parts of the communication system as well as to define how they interact.

The architecture process defines a set of plausible scenarios (Enterprise Activities) spanning the entire energy enterprise (utility, industrial, commercial and residential). The scenarios then enable analysis on the data and resulting communication requirements needed to construct a complete, high-level set of functions for the communications infrastructure to enable the envisioned functionality. The requirements can be categorized as:

- Communication configuration requirements, such as one-to-many, mobile, WAN, and LAN
- Quality of service and performance requirements, such as availability, response timing, and data accuracy

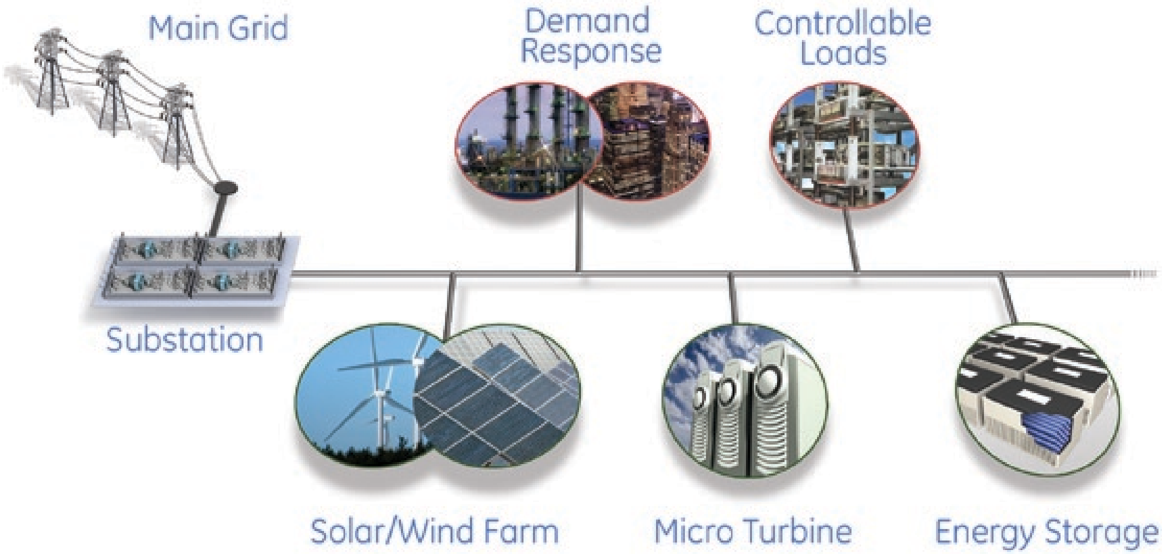

Figure 4.
Microgrid Vision

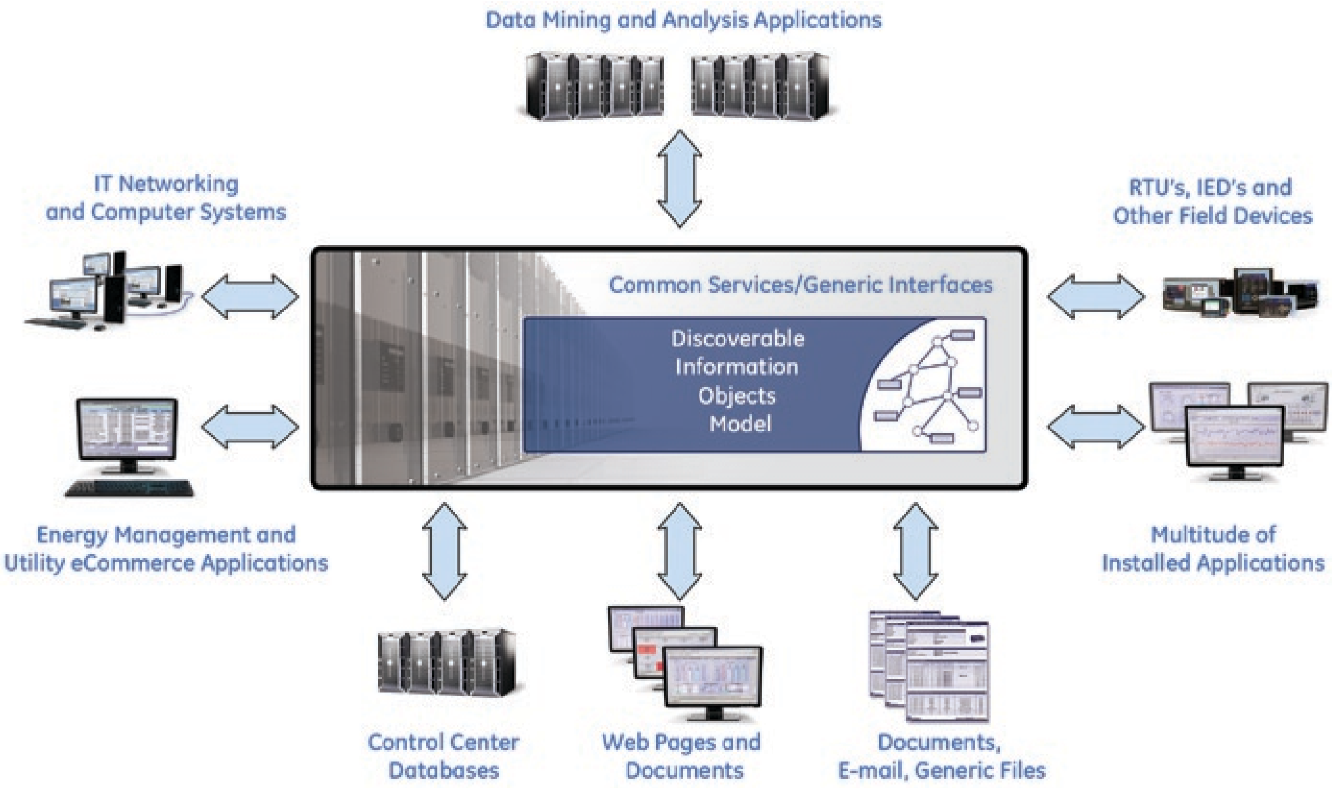

Figure 5.
Smart Grid Architecture

- Security requirements, such as authentication, access control, data integrity, confidentiality, and non-repudiation
- Data management requirements, such as large databases, many databases across organizational boundaries, and frequent updates
- Constraints and concerns related to technologies, such as media bandwidth, address space, system compute constraints, and legacy interface
- Network management requirements, such as health and diagnostics of infrastructure and equipment, remote configuration, monitoring, and control

Putting together the pieces, there are several guiding principles that show the way to an architecture. According to the IntelliGrid Architecture Report cited earlier, an architecture should be technology independent, based on standard common services, a common information model, and generic interfaces to connect it together. Figure 5 is a conceptual view of such an architecture. While adapters can accommodate the above heterogeneity, to achieve interoperability using off the shelf components, we need standards for what data is exchanged and how data is exchanged. Furthermore, these standard information models and interfaces must be applicable to a variety of utility services. A standardized common information model solves what is exchanged. A standardized set of abstract interfaces solves how data is exchanged. A single technology for every environment will never be agreed upon so adapters will still be required to convert between different technologies.

It should be noted that the IEC 61850 communication protocol, "Communication Networks and Systems for Utility Automation," meets these requirements today. This protocol defines internationally standardized models for protection, control, metering, monitoring, and a wide range of other utility objects. In addition, it defines a standard set of abstract services to read and write to these models. Most importantly, it provides a mechanism for self-description of the data models to any requesting client. This feature becomes of paramount importance for auto configuration as the number of devices in a domain becomes large, for example, millions of electric meters.

6. Conclusion

The journey towards establishing a Smart Grid is underway.

The industry is working to meet the demands of the digital society. Progress is being driven forward by demonstrating solid financial performance through reduced expenditures, meeting customers' demand for higher availability and better quality of delivery, and increasing organizational effectiveness through high-quality, timely operational information. Several application domains such as Advanced Metering Infrastructure, Smart Home, Distributed Generation/Microgrids, and Wide Area Measurement and Control are also key in driving the Smart Grid's development.

Traveling down the road to a Smart Grid will take an organized effort to overcome isolated development and unite power system organizations to provide a more capable, secure, and manageable energy provisioning and delivery system.