Standardizing the Classification of Intelligence Levels and Performance Of Electricity Supply Chains

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1 *Problem*

An electricity supply chain consists of three parts: the generation sources (various power plants), the delivery system (transmission and distribution networks), and the end customers (residential and commercial buildings, industrial plants, government and military facilities). This supply chain is quite unique: the supply and demand have to remain tightly balanced at all times, since there is no commercial solution for large-scale storage of electricity to absorb any excess power or shortfall.

In the past, much of this balancing act was done by the vertically integrated utilities that controlled both the generation and the delivery system (power grid). The power grid is the backbone of industrialized and information societies. Modern life without reliable supply of electricity is unimaginable. Like other infrastructures critical to the normal function of our daily life, the power grid needs constant care and maintenance to ensure uninterrupted service. In recent decades, the power grid in the US has become over-aged, under-invested in and overstressed. To make matters worse, the power grid is subjected to new operational scenarios and challenges never envisioned when the majority of the power grid was developed many decades ago. The main challenges:

- Deregulation unleashed unprecedented energy trading across regional power grids, presenting power flow scenarios and uncertainties the system was not designed to handle.
- The increasing penetration of renewable energy in the system further increases the uncertainty in supply, and at the same time, adds additional stress to the existing infrastructure due to the remote geographic locations.
- Our digital society depends on and demands power supply of high quality and high availability.
- Increasing incidences of unpredictable events such as wide area blackouts due to the increased stress on the system and relatively un-intelligent management systems from years gone by.
- The threat of terrorist attacks on either the physical or cyber asset of the power grid.
- The demand for increasing energy efficiency to better utilize existing assets and to reduce green house gases.

In an attempt to address these grave challenges, the power industry, vendors, research communities, consumers, federal and state government agencies have started many initiatives, all with similar objectives of making the electricity supply chain capable of meeting these technical, environmental, and security challenges. Many consortia have been established, such as SmartGrid, Modern Grid Initiative, GridWise, Green Grid, and EPRI's Intelligrid. The growing consensus is that these challenges cross many functional boundaries in planning, asset management, operation, monitoring, protection, and control; and the coordination and optimization of these complex interdependences can only be achieved through increasing the intelligence of the electricity supply chains, i.e., intelligent power grids and intelligent loads/consumers.

It is clear that the electricity industry should strive to increase the intelligence level of the electricity supply chain. But the exact meaning of an intelligent electricity supply chain element and the way this intelligence should be measured remain unclear. Without a set of clearly defined levels of intelligence articulated at reasonable granularity, grid intelligence will continue to be a fuzzy concept that will do little to the advancement of the common objective of promoting grid intelligence.

This white paper describes the seminal structure of a framework for characterizing the intelligence levels of electricity equipment in terms of measurable and technology neutral attributes. We believe that building this framework with the participation of different stakeholders will provide a common set of vocabulary for more effective communication, as well as objective standards and the ability to measure progress and success.

In this paper an Intelligent Electricity Supply Chain is defined as a system that is able to assess its health in real-time, to construct predictive views of the chain's future evolution using both real-time and off-line information, and to institute corrective measures to ensure optimal operation, which can be measured in terms of efficiency, reliability, adaptability, security, and sustainability.

2 *Challenges*

The electricity supply chain is a complex and expansive system consisting of numerous primary elements interacting continuously through electrical, magnetic and mechanical forces, and a multitude of secondary sub-systems that measure and control these interacting elements. The interplay of physical laws governing the system, combined with the randomness of demand changes in real time, creates much more complex interaction behavior than those found in other systems, such as transportation or communication systems.

To effectively control a system, reliable measurements/estimates of the system's states are needed. Large and uncertain communication delays in a power grid spanning huge distances had been a major obstacle to reliable and consistent system-wide measurements until recent years. Consequently, the controls in a power system are traditionally done locally using local measurements. Any intelligence (protection, control, optimization algorithms) exists only at the local level and is executed with little or no consideration of other control actions and their consequences elsewhere in the system. The lack of intelligence at higher levels, i.e., global information and coordination, often results in suboptimal control at best and unintended interaction with adverse effects at worst. Here are a few of the many examples where intelligence beyond the local level offers the only hope of solving a problem without causing new complications:

- Inter-area oscillation is a problem where generators located in one part of the power grid oscillate with respect to generators in a different part of the grid, which leads to a large amount of power sloshing back and forth in the system, causing extra stress on the generators and potentially destabilizing the system. The oscillation can only be effectively eliminated with intelligent control devices that use wide-area measurements and work cooperatively.
- Proper reactive power scheduling on distribution systems is essential to maintaining acceptable voltage profiles and minimizing energy losses. The schedules of reactive resources at different locations on distribution feeders cannot be made properly without the availability of real time consumption information and intelligent coordination of the control actions.
- When a fault occurs in the system, quick fault isolation and service restoration will help to minimize customer service interruption. To restore service to as many customers as quickly as possible, the real time status of the network connections and demands need to be considered to generate optimal restoration plan and switching sequences.
- When major generators go out of service unexpectedly, the resulting power imbalance could lead to the destabilization of the system, if left unattended. Having millions of end user appliances that can respond intelligently to the frequency drop can eliminate the need for customer service interruptions.

- The proliferation of high power density, enterprise-class data centers in a digital society presents many challenges and opportunities for demand reduction, power profile optimization, integration of renewable energy, and even emergency capacity to the interconnecting utility. The huge potential energy efficiency improvement, peak demand reduction, and other operating benefits cannot be fully tapped without intelligent communication, control, and coordination between the energy management system of the data center and that of the host utilities.

It is being recognized that adequate solutions to many of the critical problems in power system operation, control, protection, and optimization are not possible without adequate levels of intelligence in the basic system hardware, local and regional control software.

The electricity industry is faced with the challenge of motivating investment in more intelligent elements/systems to their investors, customers, management, regulators and other stakeholders. But what does intelligent power grid (commonly referred to as 'Smart Grid') mean? And how does it contribute to the performance of the electricity supply chain? What is lacking is a clear definition that is acceptable to most, if not all, stakeholders (vendors of electrical-energy equipment and accompanying systems, end users, policy makers, regulatory bodies, academia, professional societies, and standard organizations). It is hoped that this paper will help create clear definitions, applicable criteria, and metrics that will help end users to make their energy choices, help regulators to formulate policies that encourage customers to choose services that best fit their needs; and encourage the service provider to deploy new technologies that better the performance of the electricity supply chain.

3 *Creating a Common Language*

The focus of this whitepaper is to provide a framework for classifying the levels of intelligence of each functional element/system and its contribution to the performance of the electricity supply chain. The objective is to maximize the likelihood of desirable outcomes where system performance is improved through increase in intelligence in systems and components. This idea is illustrated in Figure 1, which shows two possible evolution paths in the intelligence and performance space. Points on the suboptimal path represent situations where a particular element is extremely intelligent and optimized for its own performance, but the overall performance of the electricity supply chain is not improved. Ensuring investment in system intelligence will produce desired improvement in system performance; appropriate policy mandates and incentives are needed to direct the technology evolution along the optimal path. The optimal path represents situations where the level of the intelligence of various of system components are improved in a coordinated fashion such that, ideally, in every stage of the evolution of system intelligence, the path follows closely to the performance frontier curve, where every point has the maximum theoretical benefit to cost ratio.

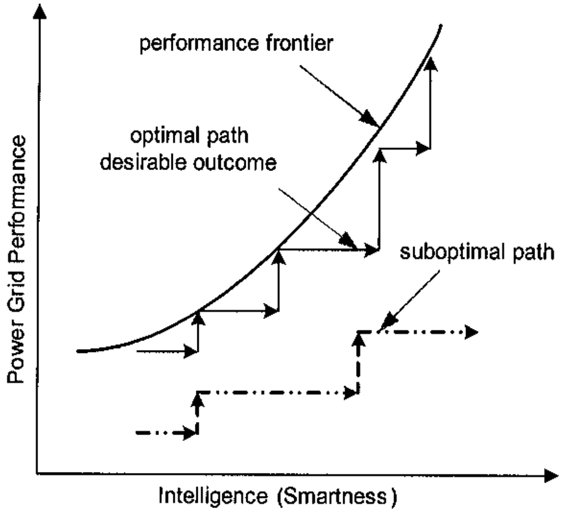

Figure 1: Desirable Evolution Path in the Intelligence-Performance Space

3.1 Factors of System Performance

The following factors have been identified as the main attributes describing the performance of the electricity supply chain (and its components):

Efficiency – How efficient is the electricity supply chain? The function of the supply chain is to transport electrical energy (converted from another form, such as coal, gas, hydro, nuclear, wind, solar, etc.) to the end customers. High performance systems should be energy-efficient, resulting in minimal energy loss during the conversion and delivery process. Significant energy savings could be achieved through optimal use of power generation resources, optimal design and operation of transmission and distribution networks, and effective demand-side management programs.

Availability/Reliability – Is the entity (device, subsystem, system) reliable/dependable and what is the quality of its output? One would expect the reliability to improve due to grid modernization. System redundancy is one way to address reliability. Loosely speaking, increased redundancy improves the reliability. However, the redundant entities must be coordinated with each other in such a way that the overall system performance is not compromised. That is, the redundant devices/systems should not work against each other. Redundancy also leads to increased cost, hence a trade-off between hardware and analytical (realized in software) redundancy should be sought. Another aspect of reliability is the quality of the output. The quality of the electricity delivered to the end customers is measured in terms of various metrics including voltage sag, power factor and the harmonic content. Lower quality of electricity can have an adverse effect on the devices and systems within the electricity supply chain.

Controllability and Interoperability – Is the entity (device, subsystem, system) controllable and interoperable with other entities? One important aspect of a modern electric power system is to provide greater observability, and by strategic placement of new actuation systems or enabling dormant elements, greater controllability of its assets can be achieved. The higher the degree of observability and controllability, the higher the overall system performance. Another important foundation in a modern power system is the interoperability that enables all of the different devices, subsystems, and agents (producers, operators, consumers, etc.) to interact beneficially and cooperatively.

Sustainability – Electricity has indeed become a basic necessity in modern society. The aim of sustainable energy development is to meet the present energy needs of the society in a way that is "sustainable" in the long run. In doing so, the ability of future generations to meet their own needs will not be compromised. Sustainable energy development requires balancing economic growth and prosperity with the preservation of the natural environment and promoting increased utilization of energy-efficient power apparatus, best practice energy management and greater use of renewables.

Security - Security can be classified into stability, physical security and cyber security. High performance systems and devices ought to be equipped with security measures to cope with the security threats and minimize the impact. Stability related security (also called robustness) is the property of an entity to sustain its operation during or following certain predefined disturbances. Cyber security or IT security is the ability to conduct eavesdrop-proof and tamperproof communication among various system components, and the ability to provide reliable authentication and authorization so that only authenticated components can perform authorized control actions. Physical security is related to physical intervention by external entities (e.g. theft or some kind of destruction of the devices and subsystems in the supply chain).

During various *planning* stages of the electrical energy system, the anticipated performance of the system can be assessed over a wide range of operating conditions and plausible changes. During the daily *operation* of the electricity supply chain, it is also important to evaluate its overall performance and the performance of its various components in real time.

Common *existing* metrics used to gauge the performance of a power system are given in the appendix. The functionality of a particular system or system components will determine the most relevant metrics.

3.2 Factors of Intelligence

The following factors have been identified as the attributes that can be used to describe the intelligence of an electric device, subsystem, and system, hereafter referred to as the entity:

- Communications – The extent of interaction and exchange of data and control parameters between entities that can help in improving situational awareness, support for industry standard communication protocol;
- Computation/Algorithms – The complexity and effectiveness of the functional algorithms;
- Sensing and Reactions – What information can the entity extract from sensed data and what does it do with the data;
- Actions – What kind of actions can the entity perform;
- Adaptability – How flexible is the entity to adapt in a changing environment? The move to require an increase in the available energy from sustainable energy resources both owned by the utilities and their customers will necessitate accommodation of this capability with the appropriate metering and safety features.

3.3 Proposed Measure of Intelligence – Level of Intelligence

These factors are difficult to measure objectively, and as a first step, it is suggested to assess the level of intelligence of the entity based on the extent of information sharing and control coordination.

The following list indicates the Levels of Intelligence (in increasing order - in this list not all levels apply to all the entities equally):

- Level 0: Primary equipment with no intelligence, such as transmission lines, cables, connectors, capacitors, insulators, generators.

- Level 1: Component-level intelligence that only has local sensing with or without local actions. Examples of intelligent components are relays, thermostats, voltage regulators of generators, tap changers of transformers, digital fault recorders, meters and breakers.
- Level 2: Master-to-slave/Peer-to-peer information exchange among devices in Level 1 to coordinate the actions of devices in a neighborhood. Some examples are distribution feeders, automated meter reading and substations.
- Level 3: Information exchange, which can result in action modification, among Level 2 masters or peer-to-peer devices in different neighborhoods, such as multiple substations.
- Level 4: Information exchange between Level 2 masters and a regional wide-area control unit. This latter unit is responsible for coordinating all the actions of the Level 2 masters in its neighborhood, such as Energy Management Systems (EMS)/ Supervisory Control and Data Acquisition (SCADA) / Distribution Management System (DMS) control centers.
- Level 5: Information exchange among Level 4 regional systems to aid in the coordination of each center's regional actions, such as cooperating control centers across a continent.

Plausible Metrics:

- Percentage of Level *i* entities in the electricity supply chain under consideration.
- A weighted average of the above percentages will yield a score for the overall Intelligence of the supply chain under consideration.

The above six levels of intelligence from level 0 to level 5 are proposed to be used as a guide to navigate the landscape of available devices/systems and in so doing, stimulate the use of more intelligence. This allows utility/regulators to measure the degree of adoption of intelligent technology and provide a yardstick for industry-wide benchmarking. For instance, if a regional system's intelligence level is at *Level x* which is the industry benchmark, but the neighboring system is at *Level x-1*, there will be perceived pressure for the deployment of more intelligence in the system with the lower intelligence level. This will also provide tangible benchmark references similar to the reliability indices in order to help drive business cases and regulatory initiatives if needed. Although the exact correlation between intelligence and performance is rather complex, having quantified system intelligence and the associated performance will help in establishing this correlation and lead to finding the optimal balance.

Using specially designed software tools and/or procedures to evaluate/benchmark if an element/system adheres to the corresponding standards (efficiency, reliability, controllability, inter-operability, security, sustainability, safety, etc., as described in a.), utilities, vendors, independent consulting firms, and regulating bodies can gauge/improve/enforce the intelligence degree of the system.

3.4 Benefits of a Common Language

The proposed framework provides metrics for evaluating the system intelligence for correlation with system performance. Knowledge of the present intelligence level of the system will stimulate the modernization and enhancement of the supply chain by incorporating new system elements that have additional intelligence. This will, in turn, steer rejuvenation of an aging power system to favor installation of more intelligent devices, without compromising the existing performance. The enhanced intelligence will also allow incorporation of novel functionalities that can lead to paradigm shifts in how the electricity supply chain is managed. The more the intelligence in the electricity supply chain, the more it will be prepared to incorporate advancements in relevant technologies (such as communication, control, etc), thus making it more agile. As the evaluation framework allows the quantification of system's intelligence, comparison of the intelligence level of one system with that of its neighboring system (control area, for instance) will become feasible. The continuing pressure to extend the capability and the performance of the aging grid at an acceptable cost will lead to the desire for incorporation of increasingly more intelligent elements in the system and help create a plausible business case.

4 *Examples*

The examples included here are used to illustrate the needs and benefits for intelligent technology to solve various power grid problems. Some of these solutions are already available and can be seen as a good start. There is still much room for improvement. In these examples it is shown how these existing solutions would be classified according to the Intelligence Levels proposed in the previous section, and how these solutions contribute to the performance of the electricity supply chain.

4.1 Real Time Transmission Capacity - building an accurate foundation for the Intelligent Grid

A primary goal of elevating today's transmission grid to an Intelligent Grid is to maximize and manage the power transfer capacity of the grid. Capacity is the foundation upon which all grid management is built. The more completely and accurately the grid capacity is known, the more effective will be all elements of the Intelligent Grid.

A transmission grid's capacity is not constant and is primarily constrained by three elements: stability, voltage limits, and thermal ratings. All three are critical, and a successful intelligent grid must have a firm grip on all three elements. Of the three, thermal ratings represent the greatest opportunity to quickly, efficiently, and economically expand the grid's capacity.

A transmission line's thermal rating is the highest current at which a line can be operated without violating safety codes, integrity of the line materials, or reliability of operation. Traditionally, thermal ratings have been assigned a fixed value based on worst case weather conditions, i.e., high ambient temperature, high solar radiation, and low wind speed. Real time ratings are developed to reflect actual weather conditions in real time. The use of real time ratings usually produces capacity increases of at least 10-15% for 95% of time and of at least 20-25% for 85% of time.

The addition of real time ratings to the grid requires (1) that instrumentation be installed to capture the varying weather conditions along the transmission line, (2) that data from the instrumentation be converted to real time ratings, and (3) that the ratings be delivered to personnel or other smart entities who will be able to manage the capacity and reliability of the grid even more effectively given accurate real time ratings. The following list indicates the Levels of Smartness applicable to real time ratings:

- At the component level, a sufficient number of sensors are located on and along the transmission line to capture parameters that reflect the impact of the spatial variability of weather on the rating of the line. Self diagnostic information (battery voltage, heartbeat) is also measured by the sensors.
- At a higher level corresponding to Level 3, a master unit, typically located in a substation, provides time synchronization to the Level 1 sensors. It also consolidates data from Level 0 sensors for delivery to the Level 5 regional wide-area control unit.
- Algorithms embedded in a coprocessor at the EMS/SCADA (Level 5 regional system) utilize data from the Level 1 sensors to calculate the real time rating for each monitored transmission line based on actual weather conditions. All outputs from various algorithms are delivered to the EMS/SCADA acting as input to other programs (security analysis, state estimation) or displayed to the grid operator in a preferred format. Finally, information exchange between Level 5 regional systems occurs in order to aid in the coordination of each center's regional actions.

Key benefits:

- Reliability – In addition to delivering accurate input for other Intelligent Grid technologies, real time ratings enhance the total reliability of the transmission grid on their own. They do so in several ways. Reliability is decreased any time the grid is moved off its optimum dispatch. The added capacity provided by real time ratings permits operators to safely avoid service curtailments or a system re-dispatch that would be mandatory based on conventional fixed ratings. Conversely, inadvertent clearance violations can occur when extreme weather conditions exceed the worst case weather assumptions upon which fixed ratings are based. A real time rating system gives the grid operator advance warning that a clearance violation is imminent.
- Efficiency – Real time ratings deliver increased capacity at a fraction (typically 5% - 10%) of the cost of physical upgrades. They also deliver capacity increases when physical upgrades cannot be economically justified. Economic benefits (such as access to lower cost generation) are immediate. It is not necessary to install real time ratings on all transmission lines in the grid, and mitigating only the severe thermal constraints raises the transfer capability of the entire grid dramatically.
- Sustainability – Real time ratings make maximum use of existing transmission assets without disturbing rights of way or requiring new rights of way.

4.2 Wide-Area Monitoring Systems (WAMS)

One of the recent advances in the electricity industry is the advent of the Phasor Measurement Unit (PMU) that has the ability to measure the local state of a power network directly on a fast time-scale. The value of a PMU's unique ability has been recognized by the industry, and R&D on intelligent monitoring applications that make use of this geographically dispersed state information is the focus of the North American SynchroPhasor Initiative (NASPI). A typical WAMS system (as shown in Figure 3) consists of the following:

- Multiple PMUs that are classified as devices with a Level 1 Intelligence;
- Phasor Data Concentrators (PDC) that use open communication standards accumulate and relate data from the Level 1 PMUs in its nearby vicinity. PDCs are devices classified as having a Level 2 of Intelligence;
- An operator workstation with a graphical user interface; historical data access; and intelligent stability monitoring algorithms that use information from multiple PDCs in order to bring about change to the functioning of the system with human intervention. These algorithms make the overall system be classified as having a Level 3 Intelligence.

Thus using the proposed measures of intelligence, a WAMS system charged with monitoring a specific part of a network (for instance, a power corridor such as Path 15 in the Californian Transmission Grid) would be classified as having a Level 3 Intelligence. There is a desire by many to link WAMS systems with the traditional SCADA/EMS system of a Power Transmission System, which will make the newly integrated system have a Level 4 Intelligence.

A WAMS system helps to improve the performance of a transmission system as follows:

- Efficiency – The intelligent algorithms of a WAMS system is capable of online assessment of the safety margin towards system instabilities. Today, power transfer limits are based on simulations that are conducted during the transmission system operation planning phase and are based on worst-case scenarios. Online assessment of system stability makes it possible to manage more efficiently the transfer limits, since actual operating conditions are usually considerably less limited than the worst-case condition used in the planning phase. In doing so, existing latent capacity of the system could be unleashed.
- Availability/Reliability – PMUs are more accurate and reliable than traditional SCADA measurements used to estimate the state of the system in an EMS. Furthermore, the quality of a PMU measurement is superior to traditional measurements in the sense that the actual state of the system is measured, and there is no need for estimation by an EMS (which is prone to convergence issues influencing the availability of the estimated

state information). The reliable and highly available information from a WAMS system can help in minimizing electricity outages helping to improve the availability and reliability of the electricity supply chain.

- Controllability and Interoperability – Through the use of modern, open standards for power system information exchange like OPC and IEC 61850, the WAMS system can be seamlessly integrated with substation automation systems, as well as SCADA/EMS systems already installed in a customer site.
- Sustainability - By transferring maximum possible power through the existing transmission corridors, network utilization can be improved; future extension of line installations may be considerably deferred.
- Security - Both thermal and stability limits of the system can be calculated on-line on a fast time-scale, ensuring that the system can be operated in a stable and secure fashion.

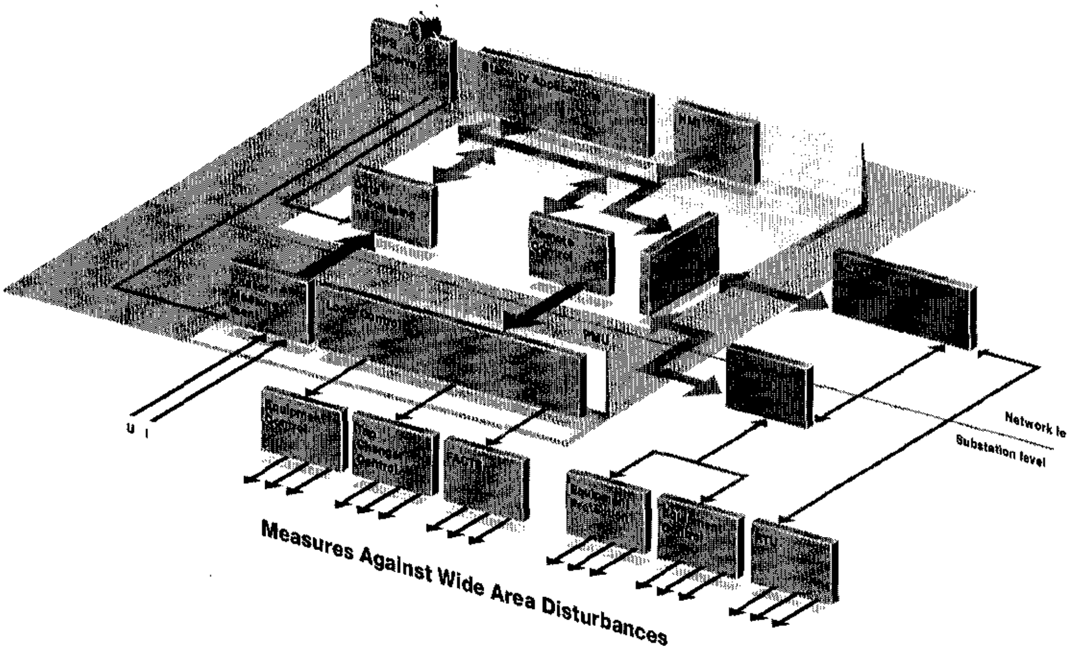

Figure 2: WAMS system setup

4.3 Distribution/Feeder Automation

In the context of feeder automation, an intelligent system entails installing devices with a Level 1 Intelligence that are capable of communicating with each other, exchanging data and taking the necessary control actions based on this data. This automatic scheme is classified as a system with Level 3 intelligence due to the information exchange between the Level 1 devices and the ability to take control actions based on the information. Intelligent electronic devices (IEDs) – Level 1 – with network-enabled communications capabilities will be installed on all switchgear, capacitors, voltage regulators, distributed generation devices, and other feeder devices. These devices have some built-in intelligence, where control actions can be carried out when a feeder disturbance occurs. The current state of the art is that IEDs are being installed in the field, but little is done to harness the information hidden in the raw data.

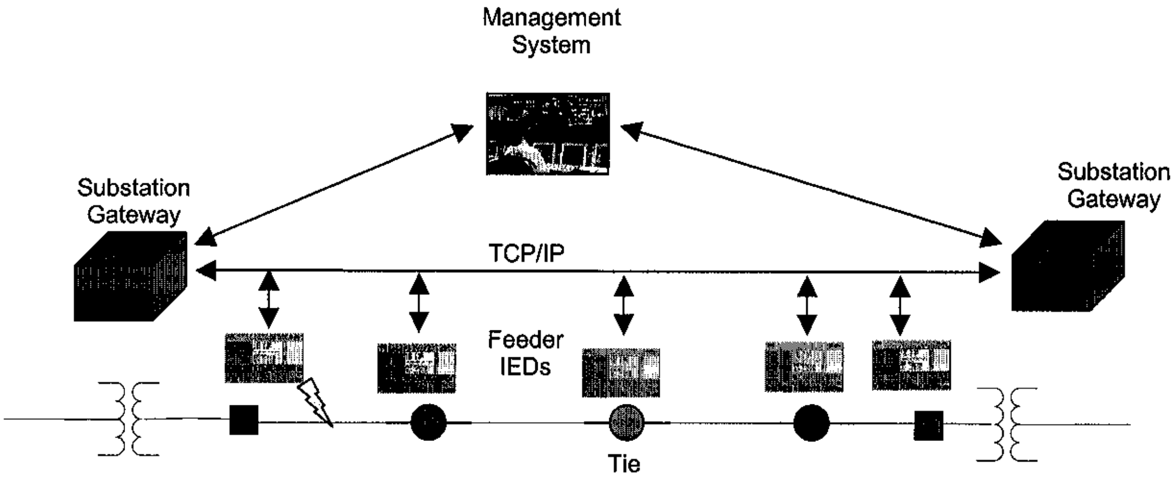

Figure 3: Hierarchical Feeder Automation

The feeder automation system must also be capable of transferring data upstream to substation automation systems and/or distribution/outage management systems, and vice versa. In this way, the distribution system becomes intelligent in that utility personnel at the network control center are able to monitor and control devices out on the feeder. Figure 3 shows an example of this type of "hierarchical feeder automation" system, where the feeder IEDs have a level of intelligence, communicate some information to a substation communications gateway, and that information is then transmitted to a distribution management system.

The benefits of such a system include:

- Improving reliability, reducing the number and duration of customer outages
- Reducing maintenance cost by minimizing the electrical/thermal/mechanical stresses on system components to prolong their service life
- Minimizing overall losses under normal operating conditions
- Enhancing knowledge by providing a communication link between different utility systems

4.4 Distributed Generation (DG) and Demand Response (DR)

Traditionally, electrical power is generated by large central power stations far from load centers and transmitted over long-distance transmission and shorter-distance distribution networks (T&D) to end users. The rights of way needed to build new transmission lines are getting more difficult to obtain due to concerns over environmental impact. Recent advancement in distributed generation (DG) technology makes it possible to build many small-scale power generators near load centers, which can be more economical and reduce the need for new transmission lines.

Renewable and alternative energy sources, such as solar- wind- or fuel cells, are the fastest growing segment in the power industry and are classified under DG. DG can be connected through an appropriate power electronic interface to the existing electricity system. The integration of DG sources into a utility's operation environment is still an active research field. Of interest are the communication protocol, information exchange, and intelligent controls required to enable the DG sources to function harmoniously with the host electricity supply chain under various operating conditions.

Demand response (DR) is the adjustment of consumer demand in response to real-time system operating conditions. DR is being recognized as an integral part of the total solution for meeting demand growth, increasing asset utilization efficiency, and avoiding unnecessary expenses building new transmission and distribution capacities.

By combining DG and DR technologies, several hundred Giga Watts of power can be made available to load centers without the need for transmission system expansion. DG, combined with advancement in energy storage, will make the loading on the T&D system more uniform, both in time and in space, which results in lower losses, better asset utilization, and more stable markets.

Key benefits:

- Sustainability – The output from renewable DG such as wind and photovoltaic is not predictable and therefore not dispatchable. As the level of penetration of intermittent power supplies increases, the reliability of power supply will suffer without energy storage and advanced energy management systems to compensate the unpredictable fluctuation of non-dispatchable energy.
- Efficiency and Reliability – A microgrid is a cluster of DG sources and DR loads that can operate in either island mode or connected to the main transmission grid. Suitable for industrial and commercial power systems, as well as expandable to advanced utility distribution systems, it provides local reliability and flexibility and increases the robustness of the T&D system. Advanced control is needed to perform rapid isolation of faults, improve power quality, automatic reclosing, and islanding by using local information for all operations.
- Controllability – In a DR program, demand level changes in response to a utility's request or price signals, providing additional control to the system operator in balancing the energy production and consumption. Figure 4 shows an example of demand response, where the system demand can be reduced by active control exercised by the customers during peak hours. Utility and owner controlled DG has existed for many years where this DG was primarily facility standby generation or from industrial cogeneration from residual process energy. The operating frequency, voltage and the protection requirements were different based upon who controlled the systems. In recent years this has blurred as Dispatchable Standby Generation, inverter based renewables, and other highly controllable sources have entered the market.

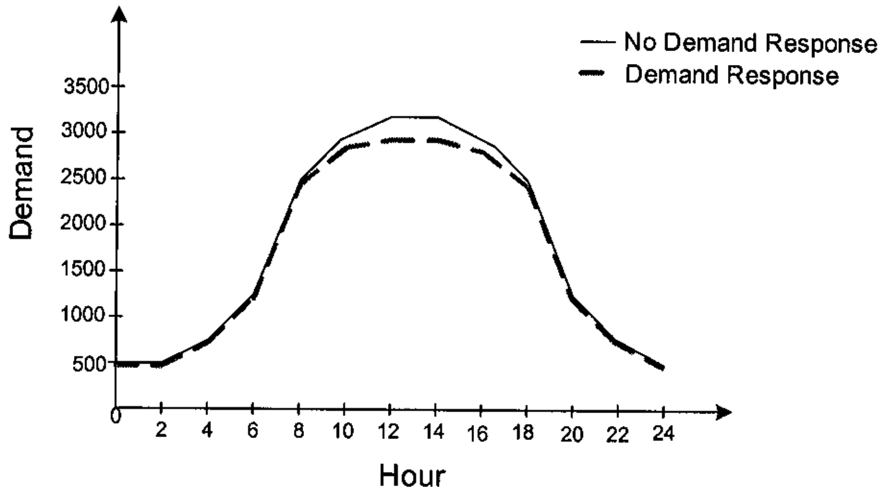

Figure 4: Demand response impact on system demand reduction

DG and DR can take on varying levels of intelligence/capability on their own. Below are some possible categories into which devices or systems could be grouped or classified:

- Simple on/off switching of circuits based upon receipt of external signals
- On/off switching of circuits based upon a system or device's inherent ability to take inputs and respond to site conditions, such as to minimize local peak demands.

- Ability of the device/system to report demand before and after a switching operation to verify the level of load that was actually reduced.
- Ability of a device/system to report perspective load not dropped but prevented from being drawn during a DR event (demand avoidance).
- Ability of DG to adapt the power delivered to aid the existing transmission and distribution system to maintain reliability/stability.

4.5 Advanced Metering Infrastructure (AMI)

AMI in the electric power industry refers to the system that measures, collects, analyzes, and controls customer energy usage by advanced metering, communication, and data management systems, as shown in Figure 5. The predecessor of AMI is automatic meter reading (AMR) technology. AMR technology provides utilities the ability to remotely and automatically collect customer meter data, while AMI technology offers full two-way communication capability, i.e., besides collecting meter data from customer sites to control center, control signals from the control center can also be sent to meters to control load at meter levels. (This control of the load is centralized control and is different than Demand Response, where the control is taken by the load itself.) AMI introduces different levels of smartness to the distribution system:

- AMI meters offer component-level intelligence (Level 1) by providing multiple functionalities, such as measuring energy consumption, recording load profiles, and monitoring voltages.
- The AMI communication network and the AMI data management system enable higher level smartness (Level 4), i.e., the information exchange via the communication network between meters and the data management system in the distribution control center.
- In addition, once the communication infrastructure is in place, it will enable other system and component automation to be implemented.

Some smart applications brought by AMI to distribution systems include automated meter reading, outage management, demand response, tamper/theft detection, and so on. Plausible metrics to measure the smartness of AMI may include (1) percentage of AMI meters in a system and (2) utility applications enabled by the AMI technology. AMI technology helps to improve distribution system performance in the following aspects:

- Reliability – AMI enhances system reliability by providing outage and restoration notifications in near real time that accelerates the outage management process and reduces power outage time;
- Efficiency – Utility applications driven by AMI, such as automated meter reading and tamper/theft detection, achieve considerable system operating cost savings;
- Controllability/Interoperability – AMI meters can monitor electricity quality at the meter level, which provides more detailed information for power quality management system to further monitor and improve power quality all over the system;
- Security – The automated meter-reading and tamper-detection functionalities offered by AMI technology can improve the safety of utility personnel simply because there is no need for utility personnel to read meter data and check the meter working status in the field.

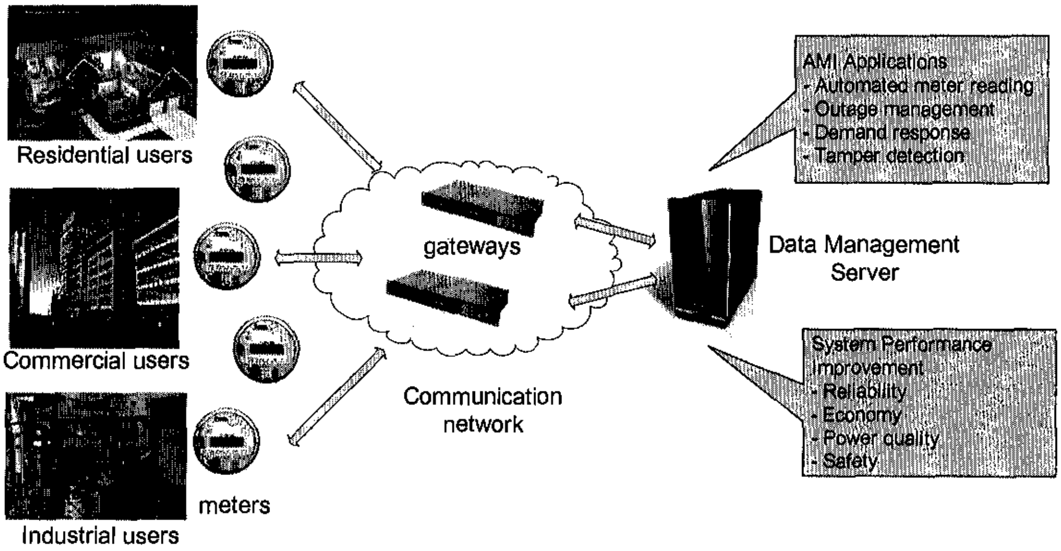

Figure 5: AMI smartness and system performance improvements

4.6 DG and DR Management for Enterprise-Class Data Centers

A unique and sizeable DG and DR potential is emerging due to the proliferation of enterprise-class Data Centers (base load of one MW or more) in a digital society. The extreme high power densities and sizeable power magnitude (to exceed 2.5% of national grid in five years) promise significant benefits through intelligent management. There may be several opportunities for intelligent integration with, and perhaps control of, data centers to enable demand reduction, demand optimization, power profile optimization, distributed generation, emergency power sourcing, and other schemes

Demand Response:

- Demand Reduction – Based upon certain advanced signals from the local grid operator, data center operators may shift loads in one site to geographically remote sites, when a local power grid experiences a demand problem. There may also be opportunities for intelligent power management systems within the data center itself with real-time monitoring of server level performance/utilization, in order to initiate on-demand virtualization where servers that have less than a predetermined load level could be collapsed onto other servers and then placed into a sleep/hibernate mode, hence reducing the center's total demand. Effective management of other major subsystems (such as the base cooling system, chiller plants, stand-by generators, and other devices) within the data center and coordination with the existing grid would require intelligent control.
- Demand Optimization – Transmission system operators, utilities, and other agencies could be given direct control over the activation of the active power management of the data center servers and other IT hardware.
- Power Profile Optimization – Given that most data centers operate with near unity PF loads, as well as having the power buffering of on-line double-conversion UPS systems, it may be possible to identify those data centers willing and able to source less than ideal commercial power, intelligently routed through local substations and switches, such that the need for grid based PF correction can be minimized.

Distributed Generation:

Data center operators are beginning to recognize the potential for solar, as well as other alternative/renewable energy sources ranging from integrated fuel-cell systems with CHP capability to micro-turbines and wind powered generators. With intelligent control system, these DG systems present several opportunities for optimized operation.

- Solar – Intelligent understanding by the grid of forecasted solar DG capacity, balanced against forecasted data center loads will better enable local power providers to plan and manage grid-level resources to augment any potential power shortfalls, as well as DG non-production periods of the day. However, it is more important that the local grid resources have the ability to recognize the availability and real-time capacity of data-center based solar DG. This real time intelligence will enable the grid to intelligently route planned excess capacity to other loads. For example, rather than shed residential peak loads, such as air conditioners, they can be left on for extended periods of peak afternoon time when solar power resources are at their maximum levels.
- Emergency Power Sourcing – Enterprise-class data centers traditionally have backup power generators that, for the majority of the time, are switched off and only turned on in an emergency when grid power is lost. With an intelligent grid control it may be possible for the grid operators to signal to the data center operator that the utility will be requiring power to be sourced either directly from the generators (where the generators will be synchronized to and back feed the grid) or to take the entire data center load off the grid. In times of peak grid capacity, both scenarios remove a significant and easily identifiable load from the grid.

5 Conclusions

This white paper is motivated by the growing industry recognition that the electrical power infrastructure in North America is seriously over-aged, overstressed, and ill-equipped to handle the multiple challenges in a digital society that fatally depends on the continuous availability of electricity. Fortunately, the great strides in recent decades in sensor, communication, computing, and information technologies enable us to transform the electricity supply chain into a more intelligent and flexible one, which will be more reliable, more efficient, and more resilient to failures and even deliberate attacks.

To promote the evolution of electricity supply chains toward this goal, this whitepaper is developed to provide a seminal framework for classifying the levels of intelligence of each functional element/system and its contribution to the overall performance of the chain. Here, only the initial structure of a framework has been sketched out. It needs to be developed further with the participation of various and many industry participants and stakeholders.

It is our vision that the development of such a framework will result in a common set of standards that the industry participants and government regulatory agencies can use to measure and promote the investment in intelligent technologies for the electricity supply chain. The common standards will enable electric power companies to construct a roadmap for upgrading technology and measuring progress, and enable regulators to benchmark system performance and design incentives to drive investment in intelligent technology in the most effective direction.

This vision will not materialize without committed, concerted effort and broad-based participation in the form of working groups and standards committees. This paper serves as a definition of a vision, as well as a call for participation to all parties interested in promoting and realizing a more intelligent electricity supply chain.

5.1 Appendix –Performance Metrics

Proposed metrics exist for Performance Factors one through to seven in the previous section. Some of these metrics are:

- Reliability:
  - Mean Time to Failure (MTTF)
  - Mean Time to Repair (MTTR)
  - System Average Interruption Frequency Index (SAIFI)
  - System Average Interruption Duration Index (SAIDI)
  - How many 9's of reliability as used in critical systems?
  - Expected Energy Not Supplied (EENS)
  - Loss of Load Probability (LOLP)
  - Availability (MTBF/(MTBF+MTTR))
  - Levels of redundancy
- Power Quality
  - Total Harmonic Distortion for both voltage and current waveforms.
  - Number of excursions beyond ITIC/CBEMA boundaries
  - Power Factor
  - Number and Duration of Interruptions
  - Other metrics defined in IEC 61000-3-2
  - Electromagnetic Compatibility
  - Electromagnetic Interference
- Safety
  - Electromagnetic Compatibility
  - Electromagnetic Interference
  - Indications as to what sort of containment/control methods are in place for events where things go wrong
  - Provide notification of people working on lines or notification of a segment that is locked-out by the system operator, etc.
- Security
  - System Stability under Contingencies
  - Cyber Security
  - Physical
  - Number of Transmission Line Rights of level 3 or above, indicating poor vegetation management around the line
  - Margins to Voltage Instability
- Economics
  - Trends of electricity prices for end customers
  - Trends of utility CapEX and O&M
  - Outage costs,
  - Improved restoration times,
  - Costs of lost productivity
  - Damaged products
- Environmental impact
  - Level of green house gas emissions for generation
  - Ratio of renewable sources in system versus total demand
  - ROW/footprint
  - MW/Mile of transmission
- Efficiency
  - Losses
  - Average capacity utilization of the network/grid
- Sustainability
  - Coarse level of supply from renewable sources