Smart Grid - A Reliability Perspective

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***Abstract*— Increasing complexity of power grids, growing demand, and requirement for greater grid reliability, security and efficiency as well as environmental and energy sustainability concerns continue to highlight the need for a quantum leap in harnessing communication and information technologies. This leap toward a "smarter" grid is now widely referred to as "smart grid". A framework for cohesive integration of these technologies facilitates convergence of acutely needed standards and protocols, and implementation of necessary analytical capabilities. The paper critically reviews the reliability impacts of major smart grid resources such as renewables, demand response, storage. We observe that an ideal mix of these resources leads to a flatter net demand that eventually accentuates reliability issues further. We then present a grid-wide IT architectural framework to meet the reliability challenges. This architecture supports a multitude of geographically and temporally coordinated hierarchical monitoring and control actions over time scales from milliseconds and up.**

***Index Terms*— Smart grid, power grid, IT infrastructure, architecture, distributed intelligence, autonomous system, software agent, global coordination, temporal coordination, execution cycle, fast local control, real-time, large-scale system, distributed system, power system operation, power system control, coordinated operation, power system security, power system reliability, self-healing grid.**

I. INTRODUCTION

THE utility industry has been utilizing advances in communication and information technology over the years in order to improve efficiency, reliability, security and quality of service. Increasing complexity in managing the bulk power grid, growing concerns for environment, energy sustainability and independence, aging asset base, demand growth and quest for service quality continue to accentuate the need for a quantum leap in application of such technologies. This leap toward a "smarter" grid is now widely referred to as "smart grid".

Smart grid (SG) is envisioned to take advantage of all available modern technologies in transforming the current grid to one that functions more intelligently to facilitate:

- Better situational awareness and operator assistance.
- Autonomous control actions to enhance reliability by increasing resiliency against component failures and natural disasters, and by eliminating or minimizing frequency and magnitude of power outages subject to regulatory policies, operating requirements, equipment limitations and customer preferences. Such control actions can be more responsive than human operator actions.
- Efficiency enhancement by maximizing asset utilization
- Resiliency against malicious attacks by virtue of better physical and IT security protocols.
- Integration of renewable resources including solar, wind, and various types of energy storage. Such integration may occur at any location in the grid ranging from the retail consumer premises to centralized plants. This will help in addressing environmental concerns and offer a genuine path toward global sustainability by adopting "green" technologies including electric transportation.
- Real-time communication between the consumer and utility so that end-users can actively participate and tailor their energy consumption based on individual preferences (price, environmental concerns, etc.).
- Improved market efficiency through innovative solutions for product types (energy, ancillary services, risks, etc.) available to market participants of all types and sizes.
- Higher quality of service – free of voltage sags and spikes as well as other disturbances and interruptions – to power an increasingly digital economy.

The momentum for the "Smart Grid" vision has increased recently due to policy and regulatory initiatives, as exemplified by [1,2,3,4]. Numerous and diverse stakeholders are striving to realize the above smart grid goals by advancing and deploying various technologies. These efforts can be categorized into the following trends:

- Reliability
- Renewable Resources
- Demand response
- Electric storage
- Electric transportation

The above trends are also recognized as priority functional areas in the "FERC Smart Grid Policy Statement" [1]. Among these trends, system reliability has always been a major focus area for the design and operation of modern grids. The other trends involve distinct smart grid resource types with diverse

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impacts on reliability. Renewable resources, while supplementing the generation capability of the grid and addressing some environmental concerns, aggravate the reliability due to their volatility. Demand response and electric storage resources are necessary for addressing economics of the grid and are perceived to support grid reliability through mitigating peak demand and load variability. Electric transportation resources are deemed helpful to meeting environmental targets and can be used to mitigate load variability. Balancing the diversity of the characteristics of these resource types presents challenges in maintaining grid reliability.

Meeting these reliability challenges while effectively integrating the above resources requires a quantum leap in harnessing communication and information technologies. A common vision for cohesive integration of these technologies facilitates the convergence of standards and protocols that are so acutely needed and expedites the deployment of the technologies. Such common vision can be arrived through a systematic approach based on understanding of reliability challenges in modern power grid as well as fundamental impacts of integrating the evolving smart grid resource mix.

This paper first provides an overview of the grid reliability challenges and then presents a critical review of the salient reliability impacts of the four smart grid resource types identified above. We observe that an ideal mix of these resources that flattens net demand would eventually accentuate reliability issues even further. Meeting reliability challenges requires a grid-wide IT infrastructure that provides coordinated monitoring and control of the grid. We then present an architectural framework for such IT infrastructure. The architecture is designed to support a multitude of geographically and temporally coordinated hierarchical monitoring and control actions over time scales ranging from milliseconds to operational planning horizon. Such capability is necessary to take full advantage of the modern measurement technologies (e.g. PMUs) and control devices (e.g. FACTS). The architecture is intended to serve as a concrete representation of a common vision that facilitates the design and development of various components of the IT infrastructure and emergence of standards and protocols needed for a smart grid.

II. RELIABILITY CHALLENGES

Reliability has always been in the forefront of power grid design and operation due to the cost of outages to customers. In the US, the annual cost of outages in 2002 is estimated to be in the order of $79B [5] which equals to about a third of the total electricity retail revenue of $249B [6]. A similar estimate based on 2008 retail revenue would be of the order of $109B. Much higher estimates have been reported by others.

The reliability issues in modern power grids are becoming increasingly more challenging. Factors contributing to the challenges include:

- Aggravated grid congestion, driven by uncertainty, diversity and distribution of energy supplies due to environmental and sustainability concerns. The power flow patterns in real-time can be significantly different from those considered in the design or off-line analyses.
- More numerous, larger transfers over longer distances increasing volatility and reducing reliability margins. This phenomenon is aggravated by energy markets.
- The grid being operated at its “edge” in more locations and more often because of:
  - “Insufficient” investment and limited rights of way
  - Increasing energy consumption and peak demand creating contention for limited transfer capability
  - Aging infrastructure
  - Maximizing asset utilization driven by modern tools for monitoring, analyzing and control
- Consolidation of operating entities giving rise to a larger “foot print” with more complex problems and requiring smaller error margins and shorter decision times. This problem may be aggravated by depletion of experienced personnel due to retirement, etc.

Massive utilization of distributed resources tends to blur the distinction between transmission and distribution, and to accentuate the complexity and volatility of grid operation.

III. RELIABILITY IMPACTS OF MAJOR SG RESOURCE TYPES

The reliability impacts of the major smart grid resource types cited above are discussed below.

Renewable Resources:

Most rapidly expanding renewable resources are expected to be wind and solar. In the U.S., wind is expected to grow from 31TWh in 2008 (1.3% of total supply) to 1160TWh by 2030 (wind energy target of 20% of total supply of 5,800 TWh) [7]. The unpredictability of wind energy resources is indicated by their low capacity factors (typically 20 to 40% [8]) which are much lower than conventional generators. Fig. 1 shows variability of a typical CAISO wind resource.

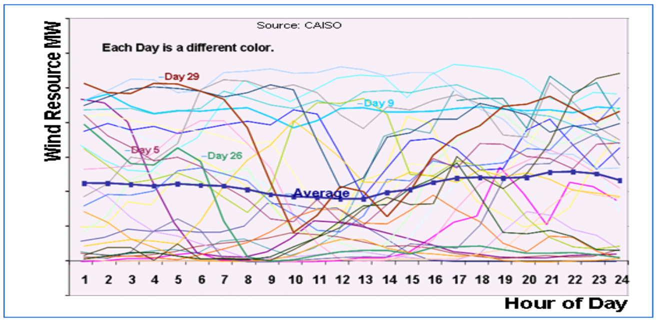
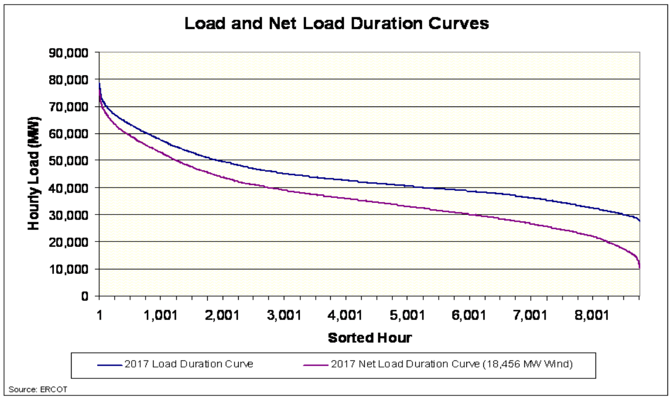


Fig. 1: Example - Variability of Wind Resource Output

This creates challenging problems in the control and reliability of the power grid. As can be seen from Fig. 2, the variability of wind energy has little correlation to the variability of the load and hence contributes only a little towards meeting ERCOT's peak load. This is despite expected 18 GW of wind capacity.



Source: ERCOT

Fig. 2: Example - Impact of 18 GW of Wind Power Capacity

The variability of wind power is impacted by the design of the equipment as well as their geographical distribution. Large scale wind resources are typically far away from loads and consequently face various transmission limitations including thermal, voltage and stability issues.

The wind power forecasting errors also present scheduling problems. The forecasting errors could be in excess of 25% depending on the terrain, forecast horizon and forecasting methodology [9]. Wind generators also present problems regarding low voltage ride through (LVRT). Wind power variability has a relatively small adverse impact on regulation requirements [10].

Solar is the most abundant source of energy. The annual solar energy reaching the surface of the earth is about 1,000 times the current world-wide fossil fuel consumption in a year [11]. Cumulative installed solar capacity is expected to reach 16GW by 2020 [12]. The two prevailing technologies to harness this energy are photovoltaic and thermal.

The variability of solar energy resources is very much impacted by climate and sunlight availability. The capacity factors for photovoltaic are typically 10 to 20%. For solar thermal plants this may reach over 70% with storage [13]. Large scale solar resources could be far away from loads and consequently face various transmission limitations. On the other hand, solar resources have a positive correlation with air conditioning load demand in warmer climates.

Renewable resources generally have adverse impact on grid reliability due to the following factors:

- Variability and low capacity factors making the net demand profile steeper (as depicted in Fig. 2)
- Low correlation with the load profile especially in the case of wind
- Relatively high forecast errors especially for longer horizons
- Congestion issues at transmission level due to large installations and at distribution level due to dispersed resources.
- Operational performance issues such as voltage and regulation

Conventionally, hydro, pumped storage and gas turbines have been used as a remedy to address the variability of the net demand. As renewables grow over the long run, increased penetration of demand response, storage devices and utilization of plug-in electric vehicles (PEVs) will complement the conventional remedies.

Demand Response / Load Management

Demand response allows consumer load reduction in response to emergency and high-price conditions on the electricity grid. Such conditions are more prevalent during peak load or congested operation. Non-emergency demand response in the range of 5 to 15% of system peak load can provide substantial benefits in reducing the need for additional resources and lowering real-time electricity prices [14]. Demand response does not substantially change the total energy consumption since a large fraction of the energy saved during the load curtailment period is consumed at a more opportune time – thus a flatter load.

Load rejection as an emergency resource to protect the grid from disruption is well understood and is implemented to operate either by system operator command or through under-frequency and/or under-voltage relays. In a smart grid, the load rejection schemes can be enhanced to act more intelligently and based on customer participation.

Price based demand response/load management as a system resource to balance demand and supply has not been widely adopted yet. Contract based participation has been typically below 5% of peak load [14]. In a smart grid, real-time price information enables wider voluntary participation by consumers. Demand response can be implemented through either automatic or manual response to price signals, or through a bidding process based on direct communications between the consumer and the market/system operator or through intermediaries such as aggregators or local utilities (Fig. 3).

In addition to capability to flatten the load profile, demand response can serve as an ancillary resource. As such, demand response schemes could improve reliability.

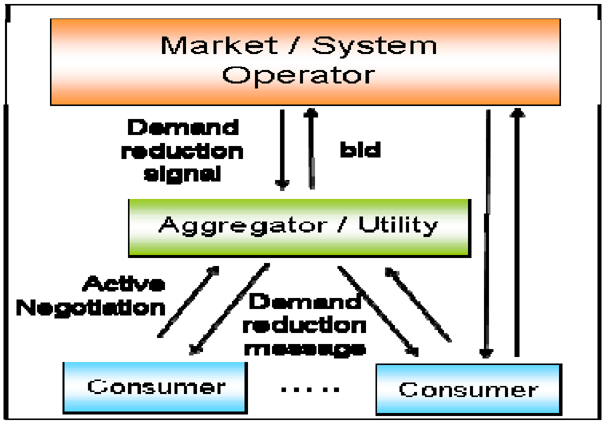


Fig. 3: Communications for Demand Response

Storage Devices

Most of the existing storage resources are hydro and pumped storage. However, growth potential for these resources is much smaller than the need for storage necessary to counter growing net demand variability presented by new wind and solar resources. Various storage technologies are emerging to fill the gap. Battery storage appears to be most promising due to improvements in technology as well as economies of scale.

Storage resources tend to make the net demand profile flatter and, as such, are expected to improve reliability. In addition, most battery storage devices can respond in sub-second time scales. Hence they can become valuable enablers of fast controls in a smart grid. Storage resources of various sizes can be distributed throughout the grid ranging from end-use loads to major substations and central power stations. This feature can help to alleviate congestion at both transmission and distribution levels.

Electric Transportation

Plug-in electric vehicles (PEV, eCAR, etc.) continue to become more popular as environmental concerns increase. They are a significant means to reduce green house gases (GHG) and reliance on fossil fuels. They will be a significant factor in load growth with a potential to eventually consume 600TWh/year assuming 30kwh for a 100-mile trip [15], and 10,000 miles per year for 200 million vehicles in the U.S. For greater adoption of all-electric vehicles, the issue of recharge time has to be resolved. Long recharge times lead to generally unacceptable level of vehicle unavailability and short recharge times have potential to increase congestion, especially at the distribution levels.

From purely reliability viewpoint, electric transportation has features similar to both demand response resources and storage resources. As PEVs present a significant factor of load growth, this can also aggravate the demand variability and associated reliability problems depending on the charging schemes and consumer behavioral patterns.

IV. ULTIMATE RELIABILITY IMPACT OF SG RESOURCES

As depicted in Fig. 4, under ideal conditions, demand response, storage and electric vehicles will be closely coordinated with all other resources such that the net load profile would be nearly flat. This implies that the grid would be operated closer to near-peak load conditions almost all of the time. Initially, flattening of the net load profile tends to improve reliability by decreasing the peak. However, over time, as the load grows, forces of optimal transmission and distribution asset utilization will push the net load closer to the system operating limits. Thus, the system will be closer to its "edge" more often, leading to higher susceptibility to failure and to accentuation of the reliability issues; hence, the need for a "smart grid" solution.

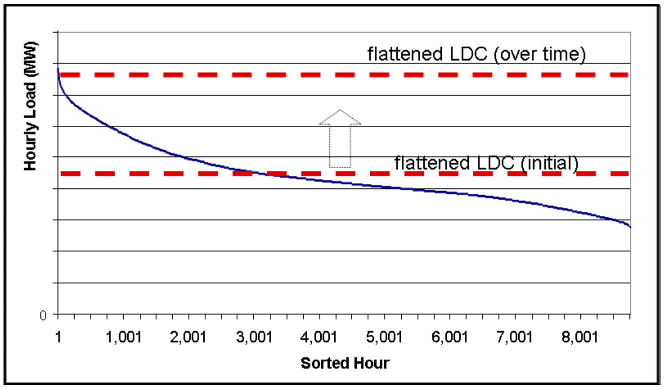


Fig. 4: Ultimate Reliability Impact of SG Resources

V. IT INFRASTRUCTURE FOR SMART GRID

Realization of the smart grid vision requires meeting the ever increasing reliability challenges by harnessing modern communication and information technologies to enable an IT infrastructure that provides grid-wide coordinated monitoring and control capabilities. Such IT infrastructure should be capable of providing fail proof and nearly instantaneous bidirectional communications among all devices ranging from individual loads to the grid-wide control centers including all important equipment at the distribution and transmission levels. This involves processing vast number of data transactions for analysis and automation. This requires a high performance infrastructure capable of providing fast intelligent local sub-second responses coordinated with a higher level global analysis in order to prevent or contain rapidly evolving adverse events. Centralized systems are too slow for this purpose. A distributed architectural framework can enable the high performance infrastructure with local intelligent sub-second response using modern technologies based on:

- Better telemetry: utilizing PMU technology for faster, time-stamped, higher accuracy, sub-second scanning to enable timely grid-wide situational awareness.
- Faster control devices: based on power electronics to enable fast automated control actions, for voltage and power flow management at both transmission and distribution levels.

- More robust controls: proactive and adaptive adjustment of protection and control settings for wide-area monitoring and controls including intentional islanding (beyond currently employed ad-hoc schemes).
- Embedded intelligent devices (IEDs): to enable adaptive and intelligent control for implementing:
    - Equipment level fault diagnosis and bad data identification
    - Operation within the constraints remotely prescribed by system operators or control centers
    - “Intelligent” RAS/SPS, etc.
    - Autonomous restoration of equipment
    - Autonomous local control actions
- Integrated and secure communications: highly distributed and pervasive communications based on open standards to allow for flexible network configurability to assure fail-proof monitoring and automation and bidirectional communications between all operators and agents.
- Enhanced computing capabilities: fail-proof and secure systems for reliable analyses to support operator decisions and autonomous intelligent functional agents orchestrated throughout a geographically and temporally coordinated hierarchy in the grid-wide IT infrastructure [16].
- Internet technology: internet protocols to facilitate data exchange, process control and cyber security to implement a standards-based distributed architecture with open interfaces. Plug-and-play hardware and software components in a service oriented architecture based on standards and technologies such as message-oriented middleware and web services to enable seamless integration of intelligence throughout the IT infrastructure ranging from equipment level IEDs to all higher levels.

Architecture

A systematic "operations driven" approach as opposed to an ad hoc "methods driven” approach is adopted for developing the architectural framework proposed above. This approach is based on consideration of all key operating concerns in categories such as performance enhancement, equipment limits, operating limits, system protection, and rapid recovery. The resulting architecture calls for distribution and coordination of the necessary functional tasks in a virtual hierarchy in three dimensions (Fig. 5):

- Organizational/Control (grid, region, control area, zone/vicinity, substation, feeder, customer, etc.) representing operational responsibilities
- Geographical area (Region 1…j, Substation 1…n, etc.)
- Functions (forecasting, alarming, voltage control, etc.)

Autonomous intelligent agents are deployed, as needed, on a grid-wide computing network throughout the infrastructure to provide services necessary for the execution of functional tasks in the areas of:

- Data Acquisition and Model Management
- System Monitoring (e.g., state estimation, security analyses, look-ahead/forecasting)
- Performance Enhancement (e.g., efficiency enhancement, corrective/preventive actions, security constrained dispatch)
- Control (e.g., AGC, automatic emergency controls, special protection schemes)

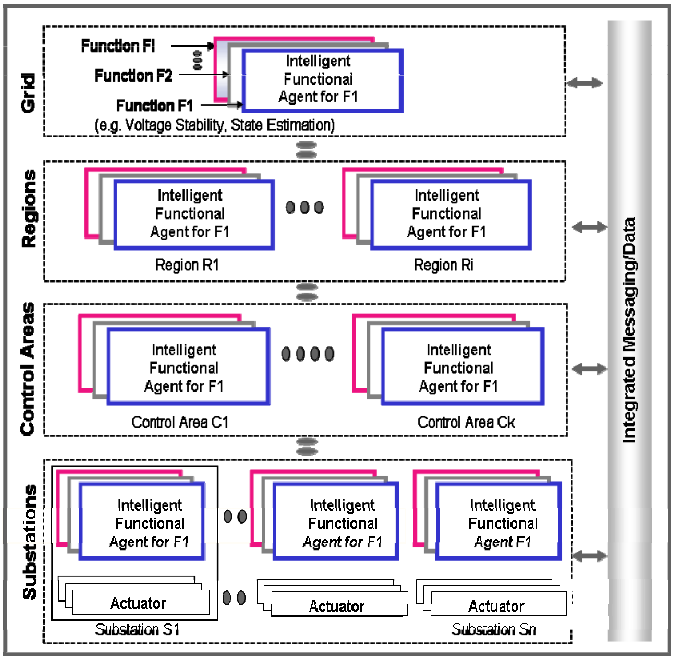


Fig. 5: Hierarchical Architecture for Smart Grid

These functional tasks potentially apply to every level from customer resource, feeder, and substation to the entire grid (e.g., a substation may perform its own share of state estimation instead of just providing raw data). The agents facilitate more ubiquitous use of local controls coordinated by global analysis, real-time tuning of control parameters, automatic arming and disarming of control actions in real-time, as well as functional coordination in the hierarchy, and in multiple timescales. The virtual architecture allows seamless integration of intelligence at all levels so that the locations of specific services and data are virtualized and transparent throughout the infrastructure subject to cyber security. Such modular, flexible and scalable infrastructure meets the global operational needs and allows for evolutionary implementation on a continental scale. It can respond to actual steady-state and transient operating conditions in real-time more effectively than conventional solutions that depend on off-line analyses.

The agents operate at different timescales ranging from milliseconds to hours corresponding to the physical phenomena of the power grid. Their actions are organized by execution cycles. An execution cycle refers to a set of related functional tasks performed in a temporally coordinated manner. The specific periods and activities of the cycles are configurable according to the operating concerns, physical phenomena, control response times, computational burden, and engineering practices. In each cycle, at each hierarchical level, an agent is responsible for a specific function and for a specific portion of the grid, as needed.

Based on the allowable latency of the tasks, the cycles can be categorized into slower and faster ones. Communications technology imposes this dichotomy at about 1-2 seconds. As such, all sub-second cycles must reside closest to the physical system. Generally, the slower cycles acquire data from larger portions of the system and perform the more extensive computations required for system-wide coordination of performance and control strategies. The faster cycles use data from a substation and vicinity to address local analytical needs to respond to rapid events subject to the control strategies developed by the slower cycles. The execution cycles interact with each other through exchange of event triggers, control parameters, performance indicators, contingency alerts, etc. A representative set of execution cycles for covering time-scales ranging from 10 milliseconds to 1 hour is depicted in Fig. 6. The specific data and algorithms required to perform a given task (e.g., demand forecast) can vary for different cycles and hierarchical levels.

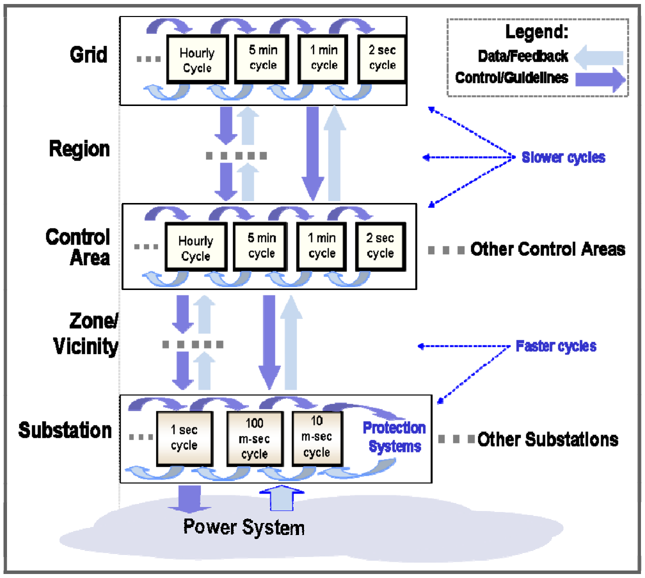


Fig. 6: Temporal Coordination by Execution Cycles

Depending on the hierarchical position of a cycle, the specific tasks assigned to the cycle may address any or all of the respective objectives. For example, the objectives at the slower cycles may include various contingency analyses and resource dispatching/scheduling activities. In the 1-second cycle, the objectives may include mitigation of slow extended oscillations. The 100-msec cycle may be focused on detecting and containing instability, while the 10-msec cycle is dedicated to executing intelligent RAS designed and deployed in slower cycles according to the relevant guidelines issued at the time of deployment.

Sub-second control actions required in the 10 or 100-millisecond cycles are made possible by the advent of synchronized measurements and FACTS based fast repetitive control actions. With accurate global data synchronized to a microsecond the challenge is to adaptively select the required data. The measurements are validated using various filtering/regression approaches (10 or 100-millisecond "state estimation" agent) at the lowest level possible (equipment level, bay level, etc.). The calculations are fundamentally different from the conventional state estimation because only about half a power frequency cycle is available for observation. The data to be estimated may include the amplitude, frequency, and phase angle associated with the instantaneous values of individual phase currents and voltages. Estimating the rates of changes of these parameters may also be critical. Non-conventional errors to be addressed may arise from phase imbalances, saturation, switching transients and a variety of other control actions throughout the system. Communication delays are a significant part of the total response time. The location of each agent in these cycles is assigned to minimize the delays considering one-way delays (about 0.2 milliseconds within a substation and 6 milliseconds between substations). For further details of the individual tasks in various cycles and levels along with the necessary analytical methods see [17,18].

VI. SYNERGIES WITH CURRENT PRACTICES

The proposed architecture provides a generalized framework that facilitates the design and development of various components of the IT infrastructure and emergence of necessary standards and protocols needed for the smart grid - especially with regard to reliability issues. The essentiality of an architectural approach in the transformation of the grid to a "smart grid" is analogous to the role of the iPhone paradigm in the transformation of the phone system from its intelligent form of the 20th century (represented by the touch-tone phone shown in Fig. 7) to its current state. It was not because of a few specific applications that iPhone revolutionized the "phone" but for its architecture that led to an explosion of functionality.

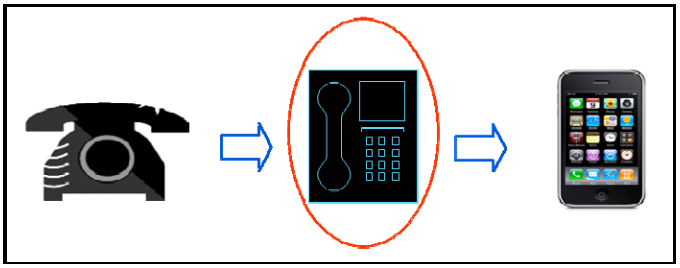


Fig. 7: Analogy for Transformational Technology

The proposed architecture enables a similar transformation of today's grid to a "smarter" grid. It provides a framework for systematic development of innovative applications and integration of new and existing applications to meet various reliability concerns, and as such facilitate integration of various smart grid resources. Implementation of the framework is technically feasible and in line with evolving industry practices.

Technical Feasibility

The technical feasibility of the architecture relies on recent advances in the areas of sensors, telecommunications, computing, internet technology, power equipment, and power system analysis. The flexibility and scalability of the design has been established through a quantitative analysis of a very large example power grid consisting of 10 regions, each with 20 control areas, and 500 substations in each area [17,18]. This analysis includes requirements for monitoring, analysis and control and excludes human interface requirements. According to the analysis, the size of data for a snapshot describing the instantaneous status can vary between 2.5kBytes for a substation to 250Mbytes for the entire grid. However the highest data transfer rate required is 8.1 MB/sec at a vicinity level (a cluster of electrically close substations). The latency for a snapshot ranges from few milliseconds at the substation to several seconds at the grid level. However, it is possible to provide a small selected subset of the information at the grid level with a 1 sec delay. In spite of the large range in the latency, using the timestamps provided by PMUs, it is possible to limit the time skew of the data at any level to 1 millisecond or even less if so desired. These requirements are entirely within the realm of feasibility using contemporary technologies.

Industry Trends

The proposed architecture is in synergy with current industry practices. Many of the technologies needed for the smart grid are already in place in various ad-hoc implementations. Examples of such implementations include wide-area monitoring and control, special protection schemes, state estimation and forecasting.

Wide-area monitoring and control has been gaining world-wide interest. This involves gathering data from and controlling a large region of the grid through the use of time synchronized phasor measurement units (PMUs). The key application areas include [19]:

- Phase angle monitoring
- Slow extended oscillation monitoring
- Voltage stability/transfer capability enhancement
- Line thermal monitoring /dynamic rating
- PMU augmented state estimation
- Geomagnetic disturbance recognition

Currently North American SynchroPhasor Initiative (NASPI) is sponsoring efforts for design and development of a robust, widely available and secure synchronized data measurement infrastructure for the interconnected North American electric power system. The design of a data highway (NASPInet) is underway [20].

Special protection scheme/remedial action scheme (SPS/RAS) systems are proliferating. They can be seen as precursors of intelligent agents. In current implementation the arming/disarming of the schemes is not adaptive. They are usually customized and too expensive to build and maintain. The proposed architecture will improve their effectiveness through frequent updates from a higher-level and greater use of local intelligence; hence intelligent SPS/RAS or iSPS/iRAS. It will also help bring down cost through use of plug-and-play components at all levels. The architecture also provides for near real time coordination of numerous schemes and control actions. Such coordination is also being pursued in ad-hoc manner by the industry [21, 22].

The state estimator function provides reliable knowledge of the current operating condition of the power system for the operator and is used by all analytical functions requiring that information. In current practice, since all analytical functions are centralized, a typical state estimator is also centralized. In order to provide intelligence throughout the grid, timely state estimation must be available at local levels for all required execution cycles/time scales (including sub-seconds). As such, it is essential to have a distributed state estimator where state estimator functional agents at every level of the three dimensional hierarchy enable local analysis. For example, a substation level agent retrieves necessary data from the local substation and other substations within the "electrical" vicinity. It resolves topology errors, identifies and rejects erroneous measurements and when necessary, obtains substitute data from other functional agents (e.g., bus load estimation or forecast) at the substation level or other levels. Other higher level agents have to coordinate their estimation with lower level solutions for a prescribed time tag. This enables a well coordinated scalable methodology.

Demand and resource forecasting is usually done at a macroscopic level such as control area and load zone. However, as need for more discrete and intelligent local control increases, better forecast at the local level will be required for demand and distributed resources. The proposed architecture provides for forecasting agents throughout the grid to communicate and access required data and information to produce more accurate load and generation models throughout the system. For example, at the substation level, the agents may forecast data for the bus loads and resources. Any operating constraints suggested by higher-level agents have to be accounted for n the forecast data. Agents at higher levels can have lower level data folded into their own forecast. This enables improvement of asset utilization and control at various levels.

Major standards initiatives are underway sponsored by

NIST [23] and IEEE (IEEE 2030 [24]). We believe these efforts would converge sooner if a common vision for the smart grid architecture is shared by all parties.

VII. CONCLUSIONS

Smart grid is primarily envisioned as a quantum leap in harnessing communication and information technologies to enhance grid reliability and to enable integration of various smart grid resources such as renewable resources, demand response, electric storage and electric transportation. Based on a critical review of the reliability impacts of these resources, it is concluded that an ideal mix of the smart grid resources leads to a flatter net demand that eventually accentuates reliability issues further. Thus the centrality of meeting reliability challenges in the realization of the smart grid is underscored.

Meeting these challenges requires a systematic approach to develop a common vision for cohesive grid-wide integration of the necessary IT technologies. An architectural framework is proposed to serve as a concrete representation of such common vision to facilitate the design, development, and grid-wide integration of various components as well as the emergence of standards and protocols needed for a smart grid. This architecture supports a multitude of fail-proof geographically and temporally coordinated hierarchical monitoring and control actions over time scales ranging from milliseconds to operational planning horizon. The architecture delivers high performance through a virtual hierarchical operation of a multitude of software agents and services in organizational, geographical and functional dimensions. This high performance infrastructure can be thought of as a "super EMS" consisting of a network of networks. The conceptual design allows for evolutionary implementation of the infrastructure.

An architectural approach is essential to the transformation of the grid to a "smarter grid" as the iPhone architectural paradigm was in the transformation of the phone. It was not because of a few specific applications that iPhone revolutionized the "phone" but for its architecture that led to an explosion of functionality.

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IX. BIOGRAPHIES

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