Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid

Context for Grid Architecture Development

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GMLC-1.2.1

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January XX 2019

ORNL/TM-XXXX/XX

Oak Ridge National Laboratory

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-XXXX/XXX

Electrical & Electronics Systems Research Division
The Center for Computational Sciences

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Date Published:

January XX, 2019

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Abstract

With increasing shifts from vertically integrated to horizontally structured operations and from centralized to distributed electric power delivery, today's electric power grid operators and designers face the challenge of creating an architecture that accommodates a host of diverse requirements. The grid's modes of operation must accommodate concerns of reliability and stability, new deployments of renewable energy sources, threats from cyber-attacks and natural disasters, and increasingly distributed system operations. Grid modernization calls for a reliable, affordable, sustainable, agile, secure, and resilient grid. However, the modernization of the U.S. power grid is hampered by mounting complexity and diverging objectives from owners and operators and is consequently highly risky and fraught with missteps. Flawed architecture, design, and implementation will lead to potential stranded investments and lost opportunities for value creation. A principled approach to minimize the risk and develop a robust grid of the future is to begin with a sound architecture for the grid to inform the design process. Architecture development starts with the context of influencing factors that provide constraints as well as driving goals. This report provides the context of emerging trends and cross-cutting systemic issues in the U.S. electric power grid and serves as part of the inputs for grid architecture development.

Acknowledgments

This material is based upon work supported by the US Department of Energy, Grid Modernization Laboratory Consortia (GMLC) 1.2.1 Grid Architecture Project, under contract number DE-AC05-00OR22725.

Contents

1.0 Introduction

It is generally believed that even today's AC electric power systems are closely rooted in the design principles of the early-to-mid twentieth century when the power grid grew with the centralizing principle of economies of scale and was constructed as unidirectional in transmission and distribution. While emerging technologies have surged and our societal structures have changed dramatically, the power grid architecture has not changed fundamentally to swiftly and seamlessly accept these changes. The grid's relative inflexibility is a source of necessary and vital stability but also creates difficulties in incorporating new developments such as increasing renewable power integration, growing man-made and natural threats on the grid, adoption of distributed energy resources and operations, and new preferences in electricity consumption.

Notwithstanding inertia in making changes in the grid, there have been increasing market-driven and policy-driven shifts from vertically integrated to horizontally structured operations and from centralized to distributed electric power delivery. Today's electric power grid operators and designers face the challenge of creating an architecture that accommodates a host of diverse requirements. The grid's modes of operation must accommodate concerns of reliability and stability, new deployments of renewable energy sources, threats from cyber-attacks and natural disasters, and increasingly distributed system operations. Grid modernization calls for a reliable, affordable, sustainable, agile, secure, and resilient grid. However, the modernization of the U.S. power grid is hampered by mounting complexity and diverging objectives from owners and operators and is consequently highly risky and fraught with missteps. Flawed architecture, design, and implementation will lead to potential stranded investments and lost opportunities for value creation. A principled approach to minimize the risk and develop a robust grid of the future is to begin with a sound architecture for the grid to inform the design process. Architecture development starts with the context of influencing factors that provide constraints as well as driving goals. This report provides the context of emerging trends and cross-cutting systemic issues in the U.S. electric power grid and serves as part of the inputs for grid architecture development.

Emerging trends are factors that are typically exogenous to the grid as is today. These could be technology, policy, or societally driven and cause the grid to evolve and adapt if and where necessary to the new trends. Systemic issues are structural and run-time conditions of grid operations that are extant in the grid and deserve to be addressed to support new requirements and objectives. Here we define the emerging trends are those drivers that create opportunities and influence future directions, and the systemic issues are those inherent in the overall system that create problems and need to be solved. Certain trends and issues can be mixed and interchangeable, which we will discuss under either trends or issues. New trends and systemic issues arise over the time. Nowadays, U.S. electrical power grid is facing challenges from aged infrastructure, natural extreme events, and cyber-attacks [1,2], and demands revolution and modernization. In the meantime, the electricity sector is shifting from traditional reliability metrics to the new resilience metric as the major risk management measures.

This document presents a listing of emerging trends and the cross-cutting systemic issues as source material for grid architecture development. These systemic issues and emerging trends are organized by the vertical categories, such as generation, load, control, protection, sensing and measurement, data and communications, modeling and analysis, operation and planning, business and market as well as grid structures and properties.

2.0 Emerging Trends

2.1 New Grid Properties

2.1.1 Increasing focus on grid resilience (A1)

With recent wide-spread extreme natural disaster events like hurricane Sandy in the U.S. east coast, U.S. grid modernization has weighted more in operational and technological approaches to improve power grid resilience, one of the new performance metrics adding to the existing metrics such as reliability, stability, security, efficiency, and affordability. Various definitions of resilience exist. In 1973, Crawford S. Holling, a Canadian ecologist, defined the resilience is a property of any ecological system which measures the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables [3]. Before this concept introduced into power systems, the electricity sector adopts reliability predominantly as the risk management measures, which is defined by NERC to be the abilities of adequacy and security [4]. In 2009, NIAC defined [5] that “infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.” In 2013, U.S. Presidential Policy Directive PPD-21 [6] uses the term "resilience" as the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions such as deliberate attacks, accidents, or naturally occurring threats or incidents.

While the framework [7-9] of power system resilience and the quantitative metrics [10,11] to measure the resilience at both power transmission and distribution levels are still evolving, various grid hardening and operational approaches have been adopted by utilities. With today’s technology maturity and the availability of hardware infrastructure invested by the smart grid funds, power system operation can be optimized to further improve system resilience without breaking the regulatory and cost constraints. But a long-term resilience vision is to shape the future power grid structurally and intrinsically adaptable and elastic to continuously changing and dynamic conditions from either climate or cyber events. Fig. 1 illustrates different network architecture [12], and from network perspective, a distributed architecture demonstrates more resilient salience. We can envision the future power grid will be moving towards distributed power systems with systems-in-system structure and flatted grid architecture.

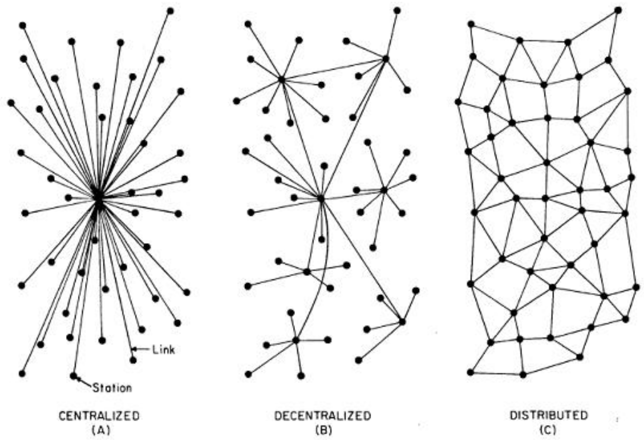

Fig. 1. Different network architecture [12].

2.1.2 Increasing focus on grid physical and cyber security (A2)

Cyber-physical security is another increasingly important modern grid property. A cyberattack that successfully disrupts grid operations would be difficult but not impossible. With the 2015 power grid incident in Ukraine, attacks on power grids are no longer a theoretical concern [2]. Smart grid has applied communication and digitization technologies and poses vulnerability for an adversary to exploit under various circumstances. In 2009, U.S. Department of Homeland Security has published a report on cyberspace policy review. In 2011, U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, updated its roadmap to achieve energy delivery systems cybersecurity. In 2018, a new dedicated Cybersecurity, Energy Security and Emergency Response Office is established under DOE to support its expanded national security responsibility.

2.2 Network Convergence

2.2.1 Gas-electricity convergence and connections of midstream gas-fired generation (B1)

Small (less than 20 MW) gas-fired generators are increasingly connected to natural gas pipeline at midstream points, instead of at the typical downstream delivery points. This allows the generator operator to purchase gas more cheaply than from endpoint suppliers and allows "shallow” suppliers to have a path to market that was blocked due to gas transmission congestion.

This trend leads to the implications for transmission and distribution (T&D) planning; that is the need of coordination with gas infrastructure to decrease congestion in both electric transmission and gas transmission. Co-optimization of gas energy and electricity may also help improve energy efficiency and avoid peak demand in the wholesale market.

2.2.2 Continuing convergence of information and communication technologies with power grid (B2)

The information and communication technologies (ICT) impact all levels of the grid, consumers, and utilities, thanks to the decreasing cost of both computing and networking, the synergy of combined computing and networking, and the prevalence of embedded computing in a wide variety of grid and edge devices.

This ICT-power grid convergence implies common architecture for synergy, and development of new value streams, both of which are emerging in the utility world, e.g. the gradual move toward using communication and edge devices as application platforms.

2.2.3 Building to grid convergence (B3)

Commercial building owners and grid operators are recognizing the potential value of going beyond traditional demand response programs to allow for two-way exchange of energy services.

The issues of building to grid integration involve not only interface specifications but at a higher level, logical function specifications so that the control systems on both sides have something to say once they are able to talk to each other. There is a trend to develop a standard energy services interface (ESI) [13,14], which is based on service-oriented architecture and provides a common interface for building responsive loads to offer energy services.

2.3 Grid Structure

2.3.1 The 85% Microgrid design (C1)

Like the UCSD Microgrid Project, the evolving designs for microgrids follow the rule of thumb, i.e. getting about 85% of their energy internally, with the remainder coming from the electric grid. This is due mostly to economics. Also, there is a need to have diesel generation inside the microgrid in order to provide system inertia needed for microgrid stability. Storage has not been shown to be sufficient for virtual inertia in microgrids.

2.3.2 Modern grids evolving into ultra-large full-scale systems (C2)

The traditional vertical separation between transmission system and distribution system is becoming vague. Whole power delivery systems, taken from the interconnection level all the way past utility boundaries to connected distributed energy resources (DER) and demand response (DR), etc., have the properties of ultra-large-scale systems (ULS), meaning that the System of Systems (SoS) and similar paradigms are not sufficient to guide architecture and design for modern grids.

Power grids have System of Systems characteristics, but SoS alone does not provide sufficient insight for architectural improvement. ULS models treat systems as having (a) inherently conflicting diverse requirements; (b) decentralized data, development, and control; (c) continuous evolution and deployment; heterogeneous, inconsistent, and changing elements; and (d) normal failures. This is a much better view on power systems than SoS alone.

2.3.3 Grid structural scalability at both upward and downward directions (C3)

Grid architectural structures should be inherently scalable. There is a trend for grid to apply scalability in both upward and downward directions. The upward scalability is obvious, but it must be possible to scale downward to fit any particular utility or extended grid element and subsystem, e.g. inside a grid-responsive building.

Scalability has three dimensions:

- scalable for the number of endpoints;
- scalable for geographic range and physical complexity, e.g. service area inter-penetration;
- scalable for functional and interaction complexity (often implies computation speed requirement).

2.4 Generation

2.4.1 RPS and other regulations pushing VER penetration (D1)

The trend of changing from traditional thermal generation to renewables such as solar and wind, also known as Variable Energy Resources (VER), is supported by public policy at the Federal government level and also at the state government level through Renewables Portfolio Standards (RPS). Since wind and solar photovoltaics (PV) do not provide the rotational inertia of the traditional generation they displace, system inertia is gradually decreasing. In California, this will be accelerated by implementation of the once-through cooling regulation that will cause shutdown of coastal gas-fired plants between 2017 and 2022.

Moreover, the VER is not dispatchable the way traditional generation is, and new control problems arise for a system originally designed around the concepts of power balance and load-following generation control. Currently, the inertia reduction issue has not yet reached serious proportions in bulk power grids, but this problem is on the radar screens of several utilities such as Southern California Edison (SCE). Solutions to these problems may involve new types of grid components and controls, and re-purposing of older device types with new controls.

2.4.2 Changing fuel mix (D2)

The change from thermal generation to renewables has been underway for some time, but more recently the use of natural gas as a replacement for coal in generation has had a significant effect on utility operations. Less obvious is the effect on utility planning – for example gas pipeline planning and build-out has displaced transmission line planning and build-out to a significant degree.

Because the markets for electricity and for natural gas have evolved separately, there is also the issue of "meshing friction" when both markets must be used to support generation, as happened in the winter of 2013-2014. Basically, these markets operate on differing time scales and rule sets, so that coordinating gas fuel and pipeline services for generation in unusual peaking conditions is complex.

2.4.3 Energy storage is being added to the grid, driven by policy and need (D3)

Significant energy storage goal is in place in select regions (e.g. California goal: 1.3 GW of storage on grid by 2020). Storage costs are being driven down by technology advances and market forces. However, addition of energy storage at various scales and attached at various points in the grid hierarchy can significantly change grid operations, economics, and control requirements.

Multiple use cases for energy storage are identified. In addition to the obvious uses such as leveling out the variations of stochastic sources, storage can be used to supply certain ancillary services, e.g. up and down frequency regulation, and could be used for entirely new services such as virtual synchronous generation for replacement of lost rotational inertia.

Energy storage can be useful for augmenting system inertia via advanced control. Fast, bilateral storage combined with power electronics and advanced controls has the potential to become a standard grid element, as basic as a transformer or circuit breaker. This means it can become pervasive at all levels of the grid and can impact functionality (thereby creating new value streams) as well as reliability and resilience. At some levels, storage penetration is paced by the way in which grid services are structured into markets. New market “products” and changes in regulation will be needed.

2.4.4 Retirement of coal and nuclear plants (D4)

The recent Environmental Protection Agency (EPA) rules regarding greenhouse gas emissions from coal plants are stipulated to lead to early retirement of over 75 GW of coal fired power plants by 2020.

Retirement of coal-fired power plants and their replacement by natural gas fired ones will lead to reduced diversity of generation fleet. This will eventually lead to increase in natural gas prices, as domestic and international demand increases. Reduced diversity in generation fleet will expose customers to increased energy price volatility due to weather related events, as experienced during the polar vortex in the northeast US in December 2013.

2.4.5 Development and deployment of “smart” inverters (D5)

Controllable power electronics used in DC/AC inverters that connect some forms of distributed generation (DG) to the grid have the potential to be used as grid control devices, supplying not just real power but also reactive power and voltage support. The smart inverter concepts [15] were originally proposed for solar PV inverters to provide ancillary services and grid support functions beyond basic energy feeding and power conversion, and are now extended [16,17] to other types of DERs, e.g. energy storage.

Control of large numbers of independently owned (independent from the utility and possibly from each other) raises several control issues and opportunities that present distribution control structure does not support well. These include coordination, fairness of dispatch if a services model is used, and how to resolve load sharing in real time. More generally, power electronics offers new abilities for stabilization, enablement of storage value streams, and improved flow control, irrespective of inverter applications for DER/VER.

2.4.6 Penetration of both dispatchable and stochastic generation at Distribution level - partial inversion of the generation model (D6)

Generation (model) has traditionally been centralized and connected at the Transmission level. Increasingly, distributed generation is being connected at the Distribution level. Sources may be traditional spinning generation (like diesel, nat. gas, propane, and biomass) or non-traditional renewables, especially solar PV, and thus a mix of dispatchable and stochastic forms is evolving on distribution grids. Most of these generations are not owned by electric utilities.

As part of the RPS and VER trend, the generation model for power grids has been shifting form centralized generation connected to Transmission to a mix of that and distributed generation connected to Distribution. This shift changes grid operations drastically, introducing multi-way real power flows and other effects not included in original grid design assumptions. In addition, distributed generation may be able to offer services back to the grid operator, such as reactive power regulation.

By about 2020, almost 30% of generation in the US will be in distributed form. Due to public policies such as net metering, feed-in tariffs, etc., much of this generation can connect to the grid and impact grid operations. Even when not grid-connected, they can impact grid operations by shifting usage to non-utility sources, thus reducing the growth of demand seen by the utility, as well as demand peak size. Sudden changes in distributed generations or distributed energy resources can look to the grid control systems like step changes in load, especially when DG resides in microgrids that can island at will. While grid codes exist for electrical interconnection and protection for DG (e.g. the ones adopting IEEE 1547), control coordination is less well developed.

This also causes a split in regulatory jurisdictions as well. Is DG considered bulk generation and/or generation capacity and therefore FERC jurisdictional? How do State level and Federal regulations mesh for DG? If distribution level markets for DER are created, how do those and bulk system organized markets coordinate?

2.4.7 Bifurcation of generation into two classes: central and distributed (D7)

Partial inversion of the generation model has split regulatory oversight for generation due to recent FERC jurisdiction ruling; generation that exists at different tier levels causes tension in control regimes.

The proliferation of distributed generation attached to the distribution grid has caused generation to change from purely a bulk power system issue (with FERC/NERC oversight) to that plus state Public Utilities Commission (PUC) level regulation for distribution level generation assets, even though the distributed generation assets may be dispatched for regional system balancing purposes. This issue also has market design and control system structural and algorithmic implications.

2.4.8 DG at scale implies less volume on the transmission systems (D8)

As the generation model bifurcation continues, and as midstream generation via gas increases, there will be reduced need for electric transmission services. This seems to have implications for transmission business models and expansion planning.

2.5 Load

2.5.1 Loads are becoming responsive (E1)

Loads have traditionally been passive in terms of grid control and fairly forecastable in terms of demand aggregated to the feeder level and above. Increasingly, loads are becoming responsive, even transactive, with the penetration of Demand Response programs. Demand response has been used by the utilities for decades, mostly in conjunction with commercial and industrial customers, and mostly in a non-automated fashion.

More recently, efforts have been made to develop to create automatically responsive loads at the commercial building level, at the residential level, and even at the individual appliance level. Going forward, high speed dynamics are envisioned for local energy balance and new energy services, some offered by third-party Electric Services Operators (ESO) and potentially involving ancillary grid services. Consequently, grid and grid control as well as coordination must extend beyond the boundaries of the utility; control becomes more complex as dynamics of interactions matter at scale.

With the rise of advanced commercial building controls, behind-the-meter storage, and wide area communications, bulk power markets, and evolving approaches to "transactive" load coordination and control, the concept of building-to-grid is moving to a bidirectional multi-services model, which means it is possible that a grid-buildings convergence is forming. This will result in an emergent platform, which is a point of interdependence for buildings and grids at the control level and grid services levels, as opposed to just the electric service (to the building) level. Ultimately, this will result in the grid becoming an extended grid (involving assets not owned by the utilities) and the observability and controllability issues for grid will extend to include responsive loads.

2.5.2 Load composition is changing (E2)

Loads are changing from simple passive forms to more active forms dominated by nonlinear power supplies and by increasing embedded intelligence. In some cases, loads are increasingly nearly self-sufficient, or can perform in a net-zero energy mode over some time period. This trend involves implications for controllability and responsiveness, as well as impacts on business models, and energy value streams.

2.5.3 DG/DER/DR are hiding real demand and introducing apparent load volatility (E3)

The effect of both DG and DER is to make the demand on the grid less, but when DG and DER are not firm, as it the case with much of it, then the grid operators must be prepared to support the full load, often on very short time scales. DR can also add to this issue if used in a non-coordinated manner.

These elements effectively introduce new apparent volatility in demand, which is problematic for balancing and also distorts capacity market signals since they can make it appear that less traditional generation is needed than must actually be available to back up non-firm DG/DER.

Advanced control methods that combine bulk system and distribution issues and that simultaneously control power and energy states are needed. These must work in the context of new industry structures such as Distribution System Operators (DSO).

2.5.4 Diversity of load is expanding to diversity of generation (E4)

Traditional generation has been dispatchable (this includes fixed generation which is dispatchable by turning it on and off), while renewable sources such as wind, solar, and tidal are not dispatchable and behave in a random manner so are difficult to forecast. Traditional grid control assumes dispatchable generation and no storage. Thus, penetration of stochastic generation sources impacts grid control and economics.

The balancing problem is considerably aggravated by stochastic generation sources, as is the closely related system frequency regulation problem. Randomly variable generation is inconsistent with the load-following approach of standard balancing and automatic generation control (AGC), which is the basis for large-scale power grid control. Oversupply of power from wind or solar can cause not just balancing issues but voltage regulation problems, congestion issues on transmission, market issues (negative marginal prices for wind energy) and investment issues (large wind curtailment due to transmission capacity, balancing capacity and ramping with combined cycle gas that can be turned down to 40% as opposed to coal at 20% - this impacts Debt Service Coverage Ratio (DSCR) and causes additional equity payments from investors). Wind farms can cause small signal instability in the 12-13 Hz range. Also, some wind turbines drop offline when wind speed exceeds a maximum (e.g. 45 mph), which negatively impacts grid control stability.

2.6 Control

2.6.1 Faster system dynamics (F1)

Power system dynamics are increasing in speed and decreasing in latency requirements by orders of magnitude. The implementation of new grid capabilities has brought with great increases in the speed with which grid events occur. This is especially true on the distribution grids, although the trend exists for transmission as well. In the last century, aside from protection, distribution grid control processes operated on time scale stretching from about five minutes to much longer and human-in-the-loop was (and still is) common. With the increasing presence of technologies such as solar PV and power electronics for inverters and power flow controllers, active time scales are moving down to sub-seconds and even to milliseconds. Consequently, automatic control is necessary, and this brings with it the need to obtain data on the same times scales as the control must operate. Consequently, there is a sort of double hit: many more new devices to control, and much faster dynamics for each device, leading to vast new data streams and increasing dependence on ICT for data acquisition and transport, analysis, and automated decision and control.

All aspects of grid operation are moving faster. At the distribution level, old style distribution control was on the time scales of five minutes and longer. With penetration of solar PV and the potential for very responsive loads, dynamics are moving to sub-second and even down to the sub-cycle level, e.g. using DSTATCOM to stabilize voltage on feeders with attached stochastic DG. At the bulk power level, the 2003 cascading blackout showed that events could happen at speeds far too fast for human operators to manage and Phase Measurement Unit (PMU) data rates are now typically 30 to 60 readings per second, which is already too much for human operators to comprehend at the raw data level.

Existing person-in-the-loop control is becoming unsustainable; existing control systems and related applications are becoming unable to keep up with real grid behavior. Additionally, data acquisition is impacted since latency and latency skew become much more significant as control time cycles decrease. The need to synchronize sampling is not just about being able to compare phase, it is also about being able to assemble a state snapshot that does not have significant errors due to sample time skew.

2.6.2 Hidden feedbacks and cross-coupling (F2)

As more advanced grid applications and systems are developed and deployed, there are increasing opportunities for system interactions. These interactions are inevitable, contrary to the apparent viewpoints of some application developers. These interactions occur and will continue to occur because the grid itself constitutes a hidden coupling layer for all grid systems and subsystems.

The coupling occurs due to the electrical physics of the grid and this coupling propagates at nearly the speed of light in most cases. Such coupling can cause effects ranging from reduced effectiveness of a smart grid function, up to and including wide area blackout. Generally, effects of such interactions will not be important at the scale of pilot projects and demonstrations but will become significant as penetrations pass tipping points.

2.6.3 Evolving control system structure (F3)

Utility control systems have traditionally been centralized, with hub and spoke communication to remote subsystems and equipment as needed. As the various trends cited here have emerged, the need for changes in control system structure has become apparent. Specifically, control systems must change from being centralized to a hybrid of central and distributed control.

While the industry generally recognizes the need for a transition to more distributed forms of control, this cannot happen without vendor-developed products. The vendors see thin markets and are unwilling to commit to new product development investment until they are reasonably assured of a market; the utilities are unwilling to commit to buying until they can see how new controls would work for them and what support they would see at regulators for new expenditures on controls and communications.

2.6.4 Increasing complexity of grid control problems and application of optimization methods to solve them (F4)

Large scale grid control problems are becoming increasingly complex as we add new functions and requirements. In many cases, we wish to do optimization as a matter of the goals we seek to optimize load profiles, or minimize carbon emissions, for example. In other cases, we need to use optimization just to be able to solve the control problems at all. Present grid control systems are not structured for large scale optimization. The cross-tier modes are increasingly important: DER/DG should be dispatched from Balancing Authorities (VPP models). End users want to perform “selfish” control that conflicts with optimal system control but must take into account impact on distribution operations to maintain grid stability and ensure efficacy of DER, for example.

Integrated Volt/VAR control is already formulated as an optimization problem with minimization of distribution substation transformer’s load tap changer (LTC) operations as the cost function, constrained by keeping voltage in bounds. Demand response problems are increasingly being formulated as optimization problems. Electric vehicle charging control is now being formulated as an optimization problem to take into account multiple constraints. Optimization is not yet being widely applied at larger scale and across multiple utility/grid tiers but should be. It is needed to coordinate multiple controls and objectives, to take complex constraints into account, and to solve distributed control problems. Optimality is not so much the issue as is the need for tools that can accommodate huge numbers of constraints and conflicting objectives. The presence of large amounts of mixed DER constitutes a new kind of control problem for the grid. These DER overlap somewhat in capability but also have differences in capability, behavior, and economics that should be taken into account operationally. Also, DER assets have different values at the bulk system level than they do for distribution but may be used by both.

2.6.5 Loss of system rotational inertia due to replacement of traditional generation with wind and solar PV (F5)

Replacement of heavy rotating machines with high rotational inertia with these wind and solar PV sources causes an overall system level decrease in inertia. Wind turbines have low inertia and are not always available. Solar PV has no inertia, but system inertia has a stabilizing effect on the bulk system.

System and individual generator inertias play a role in transient stability via Rate of Change of Frequency (ROCOF) and in the dynamics of load sharing via droop control; loss of rotating masses on the grid gradually decreases system inertia and thus reduces system stability and increases "hunting" of the generators.

2.6.6 Increasing number and penetration of new functions especially at distribution level (F6)

Functions are connected through the grid and may interact due to hidden coupling through grid electrical physics; coupling may not be recognized until a penetration tipping point has been passed (i.e. may not show in demonstration and pilot projects)

This leads to a multiple controller, multiple objective situation where applications want to make use of the same control element or infrastructure element for differing purposes and has led to situations like over-writing of prices to devices, improper control operation, and reduced power quality as well as reliability.

2.6.7 Vastly increasing number of endpoints attached to the grid that must be managed, sensed, and/or controlled (F7)

Increasing sophistication and addition of new functions to the grid results in increasing numbers of devices with embedded processing and communication capabilities. These devices must be managed in the FCAPS sense. FCAPS is a terminology borrowed from the networking domain, meaning Fault (management), Configuration, Administration, Performance (monitoring), and Security. Those that have sensing and measurement capabilities must be read; those that have control capabilities must be commanded or otherwise directed to action.

Control systems now handle sensing and control endpoints numbered in the thousands and network management systems now handle up to about 5 million devices. Widespread DER/DR penetration implies that a grid control system may have to handle 30 million to 100 million endpoints (aligned with a popular term in the first two decades of the twenty first century: internet-of-things or IOT), which existing grid control currently cannot accommodate.

2.6.8 Growing Deployment of Power Electronics (F8)

With recent advances in wide bandgap semiconductor devices and high-frequency magnetic components, power electronics are approaching performance requirements for wider deployments of these technologies in the grid. As the needs of the grid components in the domain of power electronics shift from hardware performance metrics (i.e., smaller size, lighter weight, and lower cost) to more control, more functions, more integration, more flexibility, and more commonality, the value of the deployment of new power electronics capabilities is increasing. The grid is a major emerging application for power electronics, and the industry is aiming to deploy power electronics components broadly – from high-penetration power electronics for transmission backbones (e.g., HVDC and FACTS) to grid edges (i.e., distribution systems) technologies.

2.7 Data and Communications

2.7.1 Increasing data volumes from the grid, increasing variety of data due to diversity of device types, and increasing observability (G1)

While much of the discussion around increasing volumes of data from the grid focused on meter data, in fact that the really large volumes are coming from and will continue to grow from newer instrumentation on both transmission and distribution grids. Eventually the more than 5,000 PMUs that will be installed on the US transmission grid will produce vast volumes of data at about 1.5 Petabyte per year. The vast amounts of data from PMUs is because these are streaming devices, much like video in that they produce streams of data (as often as 60 values per second) that are used at multiple destinations. Similar technology is about to start penetrating the distribution grids, which will have orders of magnitude more streaming sensing devices than will be found on the transmission.

In addition, as interest in asset monitoring continues to increase, vast new volumes of asset health and operational data will be generated, with some to be used in real time and some to be stored and analyzed later. Finally, newer protection and control systems needed for advanced grid functionality will generate enormous volumes of sensor data that must be transported, processed, and consumed in real time and be stored for offline analysis. All told, the utility industry will experience an expansion of data collection, transport, storage, and analysis needs of several orders of magnitude by 2030.

2.7.2 New desired capabilities raise new attentions for data privacy and confidentiality (G2)

Some approaches for transactive and other large-scale coordination methods require some information from prosumers to flow in the control systems. Certain data may want to be shared in order to facilitate transactions, but general security concerns still apply. Most schemes for secondary control of large numbers of endpoints assume sharing of some kinds of data that are not shared today.

2.7.3 Meta-data management (G3)

Much advanced grid capability, especially at the distribution level requires the management of large amounts of time-varying meta-data. Most grid ICT and control systems do not handle meta-data well, but more importantly, the meta-data is often inaccurate or not available. This is a special issue for distribution connectivity because it is often poorly known (connectivity models only 50% to 80% accurate) and is the context for all distribution grid data, events, and control.

2.7.4 Latency hierarchy (G4)

Grid data is consumed by a variety of applications and these applications define latency requirements that collectively form a hierarchy. This hierarchy has significant impact on architecture of the data management, analytics, and control systems.

Some data has multiple uses and so has multiple latency requirements. Some latency requirements are so short that the data must be processed close to the source and use points. This in itself implies a distributed (or at least decentralized) architecture for grid information processing and control.

2.7.5 Timing distribution for power system control and protection is shifting from GPS to PTP-based synchronization (G5)

Many grid operations require synchronization of applications that reside in geographically dispersed locations. Such applications include acquisition and processing of PMU data and grid protection control. For PMU's it is common to have local GPS timing data, but it would be more cost effective and flexible to use precise timing distributed over wide areas via Precision Time Protocol (PTP) and the communications network.

Such timing distributed is possible via the IEEE 1588/C37.238 standard. The problem is that while very precise timing can be sent through the network, the means to get the timing into applications (NTP) without loss of precision or accuracy is lacking. Some work is being done at NIST on this issue and should be moved forward expeditiously so that product vendors and application designers can make use of it. This will allow reduced dependence on GPS and more flexibility is choosing clock sources.

2.7.6 Large-Scale Data Collection Driving Machine Learning and Automation (G6)

The growth of data analysis methods such as deep learning has led to a tremendous increase and interest in automation. Using larger amounts of data acquired from the grid and learning from patterns has created the possibility of new model-free and topology-agnostic control algorithms, rapid automatic control without a human-in-the-loop step, and significantly faster grid response to known states in the grid.

Although there is significant work remaining in creating fully automated operations in certain areas of the grid, new grid designs are being developed with the full awareness that the available computational power presents great potential to optimize and provide robustness to the grid.

2.8 Operation and Planning

2.8.1 Increasing need for advanced planning processes, methods and tools (H1)

Bulk systems and distribution systems are increasingly interactive, due to DER penetration and active load participation in grid operations. Joint planning is needed, as well as integrated resource planning.

New tools must support not only tradition planning criteria, but also include support for new market products and control/coordination approaches, as these will all be interconnected in the future grid.

2.8.2 Coordination between balancing authorities (H2)

Many balancing authorities (BAs) have participated in reserve sharing groups to benefit from increased diversity of a bigger system and thus proportionately reduced amount of operating reserves. The benefit becomes more significant as the penetration of variable generation (VG) goes up. Another form of coordination between BAs is energy imbalance market (EIM), which allows the transactions between BAs to happen at 5 to 15 minutes intervals on top of hourly schedules. EIM will help BAs to more effectively deal with the intra-hour variability brought by VG with a larger pool of resources. CAISO, PacifiCorp, BPA and many other BAs have entered such agreements or are looking into this option of building an EIM.

Increasing penetration of VG poses challenges to the balance between generation and load at both inter and intra-hour time scales. Reserve sharing and EIM both to some degree increase the pool of resources BAs can dispose in system operations, while effectively reduce reserve requirements. Therefore, significant savings will result from such and new BA coordination mechanisms.

2.8.3 T&D planning, operations, and regulation in an integrated manner as opposed to the fragmented way it is done now (H3)

Due to some of the issues listed here, it is increasingly necessary to consider T&D together, not as in the past where the distribution was treated as a load floating on the transmission.

Mitigating against this depends on a couple of factors:

- regulatory structure that separates Transmission and Distribution.
- disaggregation of the industry in general.

2.8.4 Distribution operators changing to DSO models with significant structural implications (H4)

Evolving trends in the US utility industry are causing structural changes that are resulting in a growing mismatch between traditional roles and new requirements at both distribution and bulk system levels.

Models for Distribution operators are changing to DSO models with significant structural implications. The partial inversion of generation model being caused by DG penetration, coupled with the growth of functions of microgrids and DR that mask load, and the implications of storage as a grid element mean that it is not possible to continue viewing Distribution as a simple aggregated passive load "floating" on Transmission. Changes in roles and responsibilities are being examined in the industry now and those potential changes have implications for grid control architecture.

2.9 Business and Market

2.9.1 Evolving change of business models and structure in distribution systems (I1)

It has become obvious that the penetration of new functions at the distribution level, along with responsive loads and distributed generations, is causing the original model of distribution operations to become inadequate. Proceedings in Hawaii, New York, and California are all aimed at reconsidering the roles and responsibilities of distribution grid operators as is much thought leadership in the industry at large.

The Distribution System Operator model for distribution operations is apparently taking hold in various locations, driven by the expansion of grid functions and inversion of the generation model being experienced in those locations. In some models, distribution level markets are intended to foster new penetration of DER and help manage DER-rich grids. No such markets exist and the ways in which such markets should be designed, integrated with grid controls, and regulated are as yet unresolved. The question of distribution providers as DSOs vs. independent DSOs is also unresolved.

2.9.2 Load aggregation and DG aggregation companies as power market participants (I2)

Demand response resources and distributed generation can both participate in the wholesale market, respectively, after large numbers of such devices are lumped together by aggregation companies. This will increase the elasticity of demand in the energy market and help fully and more efficiently utilize available generation resources.

Existing utility companies can perform these two roles as well as new load and DG aggregators; however, DG aggregators such as solar leasing companies often target jurisdictions and geographies where existing utility rate structure gives them a competitive economic advantage.

2.9.3 Missing money and resource adequacy particularly in regions with restructured power markets (I3)

Increasing penetration of renewable energy sources, such as, wind and solar with low or zero marginal production costs, causes energy prices to drop. Hence, conventional resources, which are needed to maintain reliability in power supply, are increasingly facing issues of reduced revenues from the provision of energy and ancillary services. The missing money problem impacts resource adequacy, as being witnessed in ERCOT and other regional markets.

While regulated utilities owning both generation and transmission systems continue to meet resource adequacy requirements under the supervision of state regulators, restructured markets are trying to assure resource adequacy through market incentives assuming the power market model works well toward this direction. The reality is that the planning reserve margin, which is an indicator of resource adequacy, has become lower in restructured power markets over years and when compared to regions with regulated markets.

The resource (in)adequacy problem is especially problematic in the context of increasing sources of energy that are inherently intermittent. The issue of missing money also arises due to increasing retail choice and distributed generation, which collectively reduce a utility's customer base, and hence, the revenues. The issue has been tackled differently by various ISO’s by either instituting long-term capacity markets (ISO-NE, NYISO, PJM) or by raising scarcity prices (ERCOT). However, most of these are stop-gap measures at best and will require a serious rethinking in the design of electricity markets. Some of the proposed solutions include letting market participants cover more than just the marginal production costs in order to recover capital and other operating costs, while allowing the markets to ensure adequate competition to mitigate market power, as well as, provide appropriate market signals for future capacity building.

Resource adequacy issue gets more complicated with increased penetration of variable generation and distributed resources, even for regulated market regions. Distributed resources pose many unknowns to the planning process of regulated utilities, as well as restructured power markets, such as peak capacity, energy, availability, etc., making it more difficult to evaluate system resource adequacy and reserve margins. For restructured markets, these resources make the evaluation of profitability of new generation resources more uncertain and difficult, which could hinder investments on new generation resources. Low energy prices caused by significant amount of variable generation threats the viability of conventional generation and discourage new developments, while the amount of dispatchable resources could be in shortage to compensate for the variability of wind and solar resources.

2.9.4 Traditional value-of-service business models evolving to adapt to new grid requirements (I4)

Some grid investment decisions, especially those related to "grid hardening" and grid resilience are based on models of the value of electric service dating to the 1980's. Investment in measures that would improve grid resilience are hampered by undervalued grid service. By updating and regionalizing these models, it would be possible to provide regulators and investors with better understanding of the public good to be achieved by making grid resilience improvements.

New models for value flow and valuation of grid services to be produced by DER and other technologies will be increasingly important to grid modernization, but the tolls and methods to perform the analyses are lacking and not standardized. An example is the approach of “value stacking” to bundle grid applications to create multiple value streams [21]. These bundled applications increase the return on investment in the period of the investment, but potentially complicate operations with the mingling of retail and wholesale services.

2.9.5 Varieties of Consumer Choice (I5)

A variety of new choices is becoming available: smart vs. dumb appliances, kind of power generation desired, engaged or disengaged, power quality level vs. cost. In addition, markets or programs for residential DR are spreading. Consumers are increasingly looking to have more local control over energy choices though private DG, and through organization via microgrids, local energy networks, and via formation of Consumer Choice Aggregators (CCAs). The CCA’s are adopted into law in MA, NY, OH, CA, NJ, RI, and IL and can act as utilities in terms of both purchasing and generating power.

Value propositions are key to which choices will become more than theoretical. The movement toward localized generation leads to utility concerns of “grid defection” and a resultant “utility death spiral.” As more people pull off the grid, the cost of supporting it would fall onto those who are not able to leave. Some distribution utilities see a need to transform themselves from power delivery channels to open access energy networks. This raises technical issues (note: grids are not structured for this), as well as regulatory and public policy issues. Social network interactions also play a role as groups of end users, consumers and prosumers self-organize. (Even the terms prosumers are beginning to be used less and being replaced by separate references to consumers and DER owners.)

3.0 Systemic Issues

3.1 Grid Property

3.1.1 Resilience: power grids are vulnerable to extreme events, including extreme weather events, cyber-physical attacks, and component failures (A1)

The resilience of power grids becomes a major concern at national level after a series of widespread and large-scale extreme events like Hurricane Katrina (2005), Irene (2011), and Sandy (2012), which have resulted in disruptive damages to grid infrastructures and major blackouts. Increasing attentions are also paid to cyber-physical attacks or equipment failures. Power grid as national critical infrastructures need to be much better at withstanding event effects without dropping services, provide better ride-through for critical loads, and greatly reduce recovery and restoration times.

While various approaches to "grid hardening" are known, the deployment of these measures depends on the ability to properly plan at both transmission and distribution (T&D) levels, as well as issues related to value of service that would assist in justifying the investments necessary.

3.1.2 Power grids are not secure (in the sense of intentional attacks) (A2)

Electric power grids suffer from both cyber and physical security challenges. Without considering the Internet of Things (IoT) and social media issues, the control systems and critical infrastructure components of the grid are exposed to a variety of attacks.

Even the best multi-layer cyber security measures and processes can be breached by determined attackers. That is assuming that best practices and solutions are in place, which is not always the case. Physical attack is problematic since much electric T&D infrastructure is exposed to the public with no more than a fence for physical access control (and this is more a public safety measure than a security measure).

3.1.3 Low reliability (A3)

Utilities use reliability indices [18] to measure the performance of distribution systems. U.S. power grids have System Average Interruption Duration Indices (SAIDI) that are 10 to 25 times that of nations like Japan, South Korea or the Nordic countries, e.g. U.S. 80 to 214, Japan 6, Singapore 2.2, Netherlands 29, Germany 15, and Denmark 25.

Reasons for reliability issues vary by region. In some areas it is aging infrastructure, whereas in others it is process issues, like lack of good vegetation management, and lack of tools. Some distribution grids have no distribution SCADA, for example, or suffer severe lack of observability.

3.2 Generation

3.2.1 Penetration of both dispatchable and stochastic generation at distribution level creating partial inversion of generation model (B1)

This issue is also identified as an emerging trend, as already discussed in Section II, Trend D6.

3.2.2 Bifurcation of generation into two classes: central and distributed (B2)

This issue is also identified as an emerging trend, as already discussed in Section II, Trend D7.

3.3 Load

3.3.1 Loads are not passive and forecastable any more (C1)

Increasingly, loads are becoming responsive, even transactive. Traditionally, loads have been passive in terms of grid control and fairly forecastable in terms of demand aggregated to the feeder level and above. While Demand Response (DR) has been around at the commercial and industrial level for decades, more recently it has been applied at the residential and small business level with low speed dynamics. Going forward, high speed dynamics are envisioned for local energy balance and new energy services, some offered by the third-party Energy Services Operator and potentially involving ancillary grid services. Consequently, grid and grid control/coordination must extend beyond the boundaries of the utility; control becomes more complex as dynamics of interactions matter at scale.

This issue is also identified as an emerging trend, as discussed in Section II, Trend E1.

3.3.2 DG/DER/DR are hiding real demand and introducing apparent load volatility (C2)

This issue is also identified as an emerging trend, as discussed in Section II, Trend E3.

3.4 Control

3.4.1 Increasing complexity of grid control problems and application of optimization methods to solve them (D1)

This issue is also identified as an emerging trend, as discussed in Section II, Trend F4.

3.4.2 Penetration of stochastic generation sources impacts grid control and economics; diversity of load is expanding to diversity of generation (D2)

This issue is also identified as an emerging trend, as discussed in Section II, Trend E4.

3.4.3 Loss of system rotational inertia due to replacement of traditional generation with wind and solar PV (D3)

This issue is also identified as an emerging trend, as discussed in Section II, Trend F5.

3.4.4 System dynamics are increasing in speed and decreasing in latency requirements by orders of magnitude (D4)

This issue is also identified as an emerging trend, as discussed in Section II, Trend F1.

3.4.5 Increasing number and penetration of new functions especially at distribution level (D5)

This issue is also identified as an emerging trend,, as discussed in Section II, Trend F6.

3.4.6 Vastly increasing number of endpoints attached to the grid that existing grid control currently cannot accommodate (D6)

This issue is also identified as an emerging trend, as discussed in Section II, Trend F7.

3.4.7 Growing inadequacy of control methods and tools (D7)

To begin with, much grid control is still done in open-loop fashion, which is problematic in itself. Most closed-loop grid controls are simple PI controls which are siloed and are known to be weak in the face of high-order system dynamics. Some more powerful tools, like OPF, are available for flow control but are not widely used. Regulation and stabilization of voltage, reactive power, and frequency are being impacted by emerging trends that make existing tools increasingly inadequate.

Traditional simple closed-loop and single-input single-output frequency domain control design methods are not able to handle multi-variable, multi-objective, multi-controller problems that are arising in grid control. Optimization methods have the ability to deal with complex performance goals and system constraints in a multi-variable environment. Note that the issue is not strict optimization (which is brittle) but the ability to get solutions to complex control problems. This approach allows relaxation of the optimization process to benefit fast solutions and provide a degree of robustness.

3.4.8 Lack of control coordination across all levels of power delivery chain (D8)

Existing grid controls do not have a strong element of coordination in general, especially across the T&D boundaries. Proper coordination (a control engineering term) must have certain properties:

- must provide element coordination to ensure convergence of control solution;
- must be scalable to full power system size;
- must respect system and organizational boundaries and allow for local goals, constraints, and optimization in line with wider system goals.

3.4.9 Standard contingency analysis, state determination, and balance/control flow tools are not adequate (D9)

The tools need more powerful methods and must be much faster to accommodate new grid functions and complexity and the need to get ahead of faster grid dynamics and be integrated into closed loop control.

Contingency analysis needs to be augmented with stochastic methods in addition to N-k methods; state determination must handle T&D jointly in unbalanced mode much faster than present transmission level tools. Tools must integrate communication networks and show effects of industry structure and regulatory and financial impacts.

3.4.10 Rigid and centralized system control (D10)

Centralized control is reaching its limits in the context of power grids, and a more flexible distributed approach is needed. Distributed control is more than decentralized; the various parts must cooperate to solve a common grid control problem to be truly distributed. such control needs a structure and a coordination mechanism – ad hoc arrangements are not predictable or even designable. A formal basis for the structure and coordination mechanism are crucial architectural issues for grid control.

3.4.11 Emerging grid control structural chaos (D11)

Due to the limits of existing controls, utilities are improvising to accommodate new functions but are violating good architectural principles in the process. Most of the chaotic changes are not yet cemented in place by significant investment, but utilities are pragmatic and will do what they can to accommodate changes while keeping the lights on. Absent better tools and methods can turn into a major inhibitor to grid modernization.

3.4.12 Alternate paths to direct secondary load control (D12)

The combination of social media and potential ubiquitous networking of ordinary objects ("Internet of Things") opens new possibilities for grid interactions that entirely bypass the grid control, communications, and security systems (and thereby all NERC CIP measures).

More than one person has pointed out the possibilities of extending the flash mob concept or simple hacker-based extortion to the control of home energy-using devices, so that significant amounts of demand could be manipulated on short time cycles to disrupt grid operations. If the IoT model of Internet-connected home devices becomes pervasive, this would potentially be a load control channel that entirely bypasses the utility, except for the electrical coupling through power circuits. The same is true for DR aggregators, but in that case, there is an organization involved (the ESO or aggregator) that could be held to some level of security responsibility. In the social media case, there is no centralized point of responsibility. How does the utility maintain grid manageability and stability under social media/IoT attack?

In terms of more traditional cyberattack, if transactive controls connect the utility to individual home devices that are also Internet connected, then a connectivity path exits form the internet to the utility. If a premise gateway is used by the utility, connectivity still exists, but now a single point of coupling exists that reduces the threat surface somewhat - this is an argument against having utilities reach into the home or business to coordinate or control devices.

3.5 Protection

3.5.1 Protection methods are becoming inadequate (E1)

Protection is largely component-based, non-adaptive, and requires detailed ad hoc knowledge and constant adjustment. Digital relays require many complicated settings and adjustments. No methods exist to derive settings automatically or even systematically and changing settings in real time to reflect changing circuit topology or system conditions is largely a theoretical concept. Protective relaying covering components, zones, areas (Remedial action Schemes, RAS) and systems (System Integrity Protection System, SIPS) requires setting large numbers of complicated relay parameters using mostly ad hoc approaches to protection coordination.

Emerging instrumentation such as synchrophasor measurement is not employed although the potential is recognized. Closing the loop in a structured way for protection at the local, zone, area, system, and backup levels is needed. Manual setting and adjustment of relay settings must be eliminated or reduced to automation.

3.6 Sensing and Measurement

3.6.1 Instantaneous frequency and rate of change of frequency not measured properly (F1)

Several protection and control functions for grids are based in instantaneous frequency (IF) or instantaneous rate of change of frequency (ROCOF). However, the methods used do not measure either of these properly.

Existing methods make measurements over significant time windows, thus computing average values rather than instantaneous values. This reduces the accuracy of Phase Measurement Unit (PMU) measurements, for example, and leads to errors where IF is used in protection. For ROCOF, the inability to compute accurate values hampers the implementation of some microgrid islanding protective schemes and will limit the ability to create virtual inertia from storage and other inverter-based devices.

3.6.2 Residential AMI not very useful for situational awareness (F2)

Residential Advanced Metering Infrastructure (AMI), i.e. smart meters, are not very useful for applications other than reporting usage a few times per day. Residential meters are designed for lowest cost and so do not have advanced sensing capabilities; this means that they do not measure many of the useful quantities needed for grid state determination; in some cases, the existing measurement are not made in a useful manner.

It is necessary with most AMI systems to go through the meter data collection head end to obtain any meter data, including voltage readings. Meter installation databases generally relate geospatial and customer information to the meter, but there is often no documented relationship to power grid connectivity; however, power grid connectivity is the context in which sensed data must be interpreted.

Residential meter systems and their communication networks can take very long time periods to re-converge upon partial or complete power restoration, so the meters do not come online fast enough to report grid state information that would be useful for restoration operations or grid control during restoration. Most residential meters do not have a strong notion of time, so that time-synchronized measurements, important for control system operation, are not possible with meters.

3.6.3 Distribution grid observability is poor; grid state definition is too limited (F3)

Distribution grids have low levels of sensing and measurement, generally are not adequate for advanced grid functions and devices. Little knowledge is available to provide guidelines for distribution grid observability strategy or design.

In a larger sense, grid state should be extended to cover T&D, but not just electrically. It should include electrical, thermal, stress, risk, financial, utilization, and security states, for example.

Synchronized measurement for unbalanced three-phase distribution circuits is needed for advanced grid integration and control but little such capability exists or has been deployed. AMI systems are not useful as distribution grid sensor networks and do not provide situational awareness on anything like a real time basis. Wireless mesh networks for distribution do not have the necessary bandwidth, latency, or fault/outage re-convergence characteristics to support advanced grid operations and do not provide the advanced protocols needed for modern sensing and control.

3.7 Data and Communications

3.7.1 New desired capabilities raise new issues for data privacy and confidentiality (G1)

This issue is also identified as an emerging trend, as discussed in Section II, Trend G2.

3.7.2 Timing distribution issue (G2)

This issue is also identified as an emerging trend, as discussed in Section II, Trend G5.

3.7.3 Limited spectrum allocation or low communication bandwidth for electric utilities does not meet new control and protection requirements (G3)

Licensing and availability of spectrum for utility operational communications is limited by the ability of telecom companies to bid up and acquire spectrum licenses in bands that would be useful to the utilities.

Police/fire/EMS groups have fought the utilities vigorously and successfully at the FCC and Congressional levels to keep utilities from getting dedicated spectrum and from getting 'first responder" status on existing wireless networks. The telco's have also fought utility dedicated spectrum successfully because they want to force the utilities to use the telco networks. The utilities have had two objections: they need first responder status and they have security requirements that may include NERC CIP. However, NERC CIP explicitly excludes telco networks from requirements if the utilities use VPN, IPSEC or other security measures for data in transit across telco networks. The other argument utilities use is that telco base stations do not have adequate battery backup for outage situations and therefore are insufficiently resilient. This issue and access are resolvable via SLA's, but the telco's have tended to try to gouge the utilities for such agreements.

Much of this could be resolved within 1 or 2 generations of technology development around software defined radios (SDR). SDR technology with enough intelligence could eliminate the need for dedicated spectrum entirely through auto configuration of band, modulation technique, etc. The present spectrum allocation/licensing situation tends to inhibit SDR, so it is developing in the context of Wi-Fi, Zigbee, etc.

3.7.4 FAN level communications technologies are not adequate for emerging advanced grid control (G4)

Field Area Networks (FAN) provide "last mile" communications for many US AMI systems and are proposed for new Distribution Automation communications. Wireless mesh FAN's, and wireless FAN's in general, have issues and limitations that make them problematic for mission-critical grid control systems.

Wireless mesh networks suffer severe performance limitations due to several factors: limited bandwidth, internal administrative traffic using much of the available raw bandwidth to keep the mesh in operation, large latencies due to packet hopping, extensive packet loss, limited protocol availability, scalability problems, and very long delays in mesh reformation after an outage.

3.7.5 Insufficient meta-data management (G5)

This issue is also identified as an emerging trend, as discussed in Section II, Trend G3.

3.7.6 Data latency hierarchy issue (G6)

This issue is also identified as an emerging trend, as discussed in Section II, Trend G4.

3.8 Analysis and Modeling

3.8.1 Existing analysis and modeling methodology are not sufficient for full-scale modern grids (H1)

The whole power delivery systems, taken from the Interconnection level all the way past utility boundaries to connected DER/DR, etc., have the properties of ultra-large-scale systems (ULS), meaning that the System of Systems (SoS) and similar paradigms are not sufficient to guide architecture and design for modern grids.

Power grids have System of Systems characteristics, but SoS alone does not provide sufficient insight for architectural improvement. ULS models treat systems as having inherently conflicting diverse requirements; decentralized data, development, and control; continuous evolution and deployment; heterogeneous, inconsistent, and changing elements; and normal failures. This is a much better view on power systems than SoS alone.

3.8.2 Existing grid architecture analysis and modeling is not scalable (H2)

Architectural structures should be inherently scalable. Scalability applies in two directions: upward is obvious but it must be possible to scale downward to fit any particular utility or extended grid element and subsystem, e.g. inside a grid-responsive building.

Scalability has three dimensions:

- scalable for number of endpoints;
- scalable for geographic range and physical complexity, e.g. service area inter-penetration;
- scalable for functional and interaction complexity (often implies computation speed requirement).

3.9 Operation and Planning

3.9.1 T&D planning, operations, and regulation is done in a fragmented way as traditionally (I1)

This issue is also identified as an emerging trend, as discussed in Section II, Trend H3.

3.9.2 Resource adequacy in regions with restructured power markets (I2)

This issue is also identified as an emerging trend, as discussed in Section II, Trend I3.

3.10 Business and Market

3.10.1 Aging infrastructure, aging workforce, and legacy systems (J1)

As is well known, the utility work force is approaching retirement and replacement has been slow. At the same time, much infrastructure is due for upgrade as it reaches end of service life. Finally, many existing legacy systems are not yet depreciated and will be in place for some time, so must be accommodated when new systems and functions are being integrated.

Some of the workforce will end up working as consultants to the utilities due to their knowledge of the systems - necessitated by not having new staff who have had time to learn the grids and systems. This helps prolong the existence of legacy equipment and systems and can lead to a kick the can approach to avoiding investment to maintain a Business-as-Usual (BAU) approach, but BAU has been shown to be detrimental to the utility over the longer run. Many utilities are reluctant to give up legacy systems until the full value has been extracted - this is a bottleneck problem with AMI, since new investment in AMI will not occur for decades in most cases, even though the current crop of AMI solutions is weak.

3.10.2 Obsolete value-of-service models (J2)

This issue is also identified as an emerging trend, as discussed in Section II, Trend I4.

3.10.3 Industry disaggregation has caused benefits to accumulate to different places from investment (J3)

Benefits related to grid investments often accrue to parties or industry segments other than those who would make the investments and so investment is held back.

This issue is part industry structure and part regulatory in nature. Present approaches do not provide a means to account for and get decision credit for benefits that accrue to a different organization, e.g. an investment at the distribution level that benefits generation or transmission.

3.10.4 Growing mismatch between traditional business roles and new market requirements occur at both distribution and bulk system operator levels (J4)

This issue is also identified as an emerging trend, as discussed in Section II, Trend H4.

4.0 Conclusion

The utility industry is undergoing a transition from simply operating efficiently with a high degree of reliability, to keeping the lights on while being resilient, flexible and agile to new requirements, clean and sustainable, economical, and cyber-physically secure. This change has added mounting complexity, e.g. grid volatility, grid structure change, fast system dynamics, more endpoints and data, on top of aging infrastructure and legacy structure, hence increasing risk to policy and investment decisions. Methods and tools are needed to help decision makers in the electric industry—such as regulators, utilities, and technology developers—manage this complexity as well as identify hidden interactions and technical gaps that could result in unintended consequences, limited benefit realization, or stranded electricity investments as changes are made to modernize the grid.

Encompassing the disciplines of system architecture, network theory, and control theory applied to the power grid, the process of grid architecture construction results in the highest-level description of the complete grid. The architecture forms a key tool to help understand and define the many complex interactions that exist in present and future grids [19,20]. Not only helping manage complexity (and therefore risk), grid architecture can assist communication among stakeholders around a shared vision of the future grid, identify and remove barriers and define essential limits, identify gaps in theory, technology, organization and regulation, and provide a framework for complex grid-related development activities. The new grid architecture discipline aims to addressing this challenge and making the complex problem manageable with a set of new architecture descriptions and associated tools that will be vital to helping stakeholders assess situations surrounding grid modernization.

The grid architecture development follows the process as illustrated in Fig. 2, which takes the inputs of requirements and constraints, architecture principles and basis, existing grid models, emerging trends, systemic issues, and use cases; defines grid qualities and properties; specifies structures and components as well as their properties; and builds mapping from structures/components to properties and to qualities.

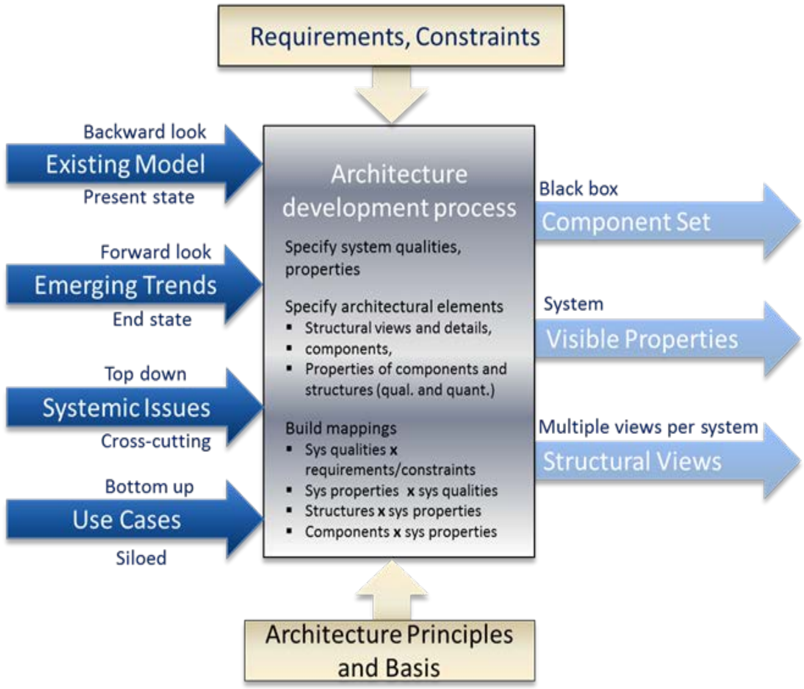

Fig. 2. Grid architecture development process[19,20].

This document provides a thorough listing of the emerging trends and systemic issues extant in power grids and provides input information for the grid architecture development as part of foundational and core activities under US DOE's Grid Modernization Initiative (underway in the 2013-2019 timeframe).

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