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Grid Architecture 2

January 2016

JD Taft

U.S. DEPARTMENT OF
ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Richland, Washington 99352

Introduction

The report describes work done on Grid Architecture under the auspices of the Department of Energy Office of Electricity Delivery and Reliability in 2015.

As described in the first Grid Architecture report, the primary purpose of this work is to provide stakeholder insight about grid issues so as to enable superior decision making on their part. Doing this requires the creation of various work products, including oft-times complex diagrams, analyses, and explanations. This report provides architectural insights into several important grid topics and also describes work done to advance the science of Grid Architecture as well.

A few of the insights to be gained from reading this report are summarized here:

- At the grid architectural level, it is much more useful to consider network convergence than just integration, especially in the context of the network-of-structures model of the grid. Identification of potential resulting value streams and the platforms that enable them can provide much stronger justifications for investment in grid modernization than simple integration can.
- In the total Distribution System Operator (DSO) model, the ISO (or RTO) is properly viewed as providing an energy service to multiple DSO nodes. The ISO and Bulk Energy System (BES) are in effect an energy "cloud" and the ISO is the energy cloud service provider for Distribution Owners (Distribution Providers).
- In a complete systems view of the grid, planning processes and associated capacity markets (where they exist) must be considered part of the overall grid management and control system.
- The potential presence of a mix of Distributed Energy Resources (DER) elements poses a new kind of grid control/coordination opportunity with as-yet unresolved complications. In addition, if some form of distribution level market mechanism is employed, the interactions between the market and the control/coordination mechanisms must also be considered, which adds another new dimension to Distribution Management System design.
- With proper formulation and layered decomposition, the Laminar Coordination method can provide the framework for market-control/coordination of the distribution assets and the DSO/ISO interface, thus providing the mechanism to facilitate high penetration of DERs in a standardized way that takes control considerations into account. In other words, Laminar Coordination can be the basis for the Transactive Grid Code for DER integration.
- As grid dynamics increase in speed it is necessary to consider sensor subsystem dynamics when determining control stability. Consequently, it is useful to consider architectural structures for sensors that minimize inherent latency.
- The introduction of market-control mechanisms (Transactive Energy) at the distribution level adds a new layer of complexity to distribution sensing and measurement architecture and design. Market products and rules must be included in the mix of sensing and measurement requirements.
- As grid dynamics and sensor data rates continue to increase, network design for grid protection and control becomes increasingly crucial. It is not sufficient for controls and communication networks to be considered together when planning a modernized grid, it is also necessary for controls and communications to be capable of working together in an interactive and dynamic manner.

The whole report provides the bases for these and many other insights as well as illustrations of the key concepts, structures, and new architectural views.

Acknowledgments

This paper was prepared for the US Department of Energy Office of Electricity Delivery and Energy Reliability. The author wishes to thank Eric Udren of Quanta Technology, LLC, Rick Geiger of Cisco Systems, He Hao, Renke Huang, and Jakob Stoustrup of PNNL, Lorenzo Kristov of CA ISO, Wade Malcolm of Omnetric Group, and Paul De Martini of the Resnick Sustainability Institute at CalTech for the many discussions and insights they provided during this work.

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1.0 Part 1: Emerging Trends Update

In the first grid architecture report done for the Department of Energy, a set of utility industry emerging trends was used as part of the input to the process for developing a few forward-looking architecture views.[1] This set of trends has been updated for the present work and the entire set of updated trends is listed in Appendix A.

In the time since the first report, the focus on the related issues of DER penetration, redefining roles and responsibilities for distribution utilities, and the application of market mechanisms ("Transactive Energy") in combination with grid control and management has increased in intensity, with a number of states actively working on grid modernization plans, including CA, NY, MN, HI, and IL. Renewed focus on planning, including integrated resource planning is developing, as planning becomes understood as an integral part of the full transactive model that spans the bulk energy system, distribution, and prosumer assets.

According to a survey[2] of over 400 U.S. electric utility executives, the following are important trends:

- The largest growth opportunities for utilities over the next five years are in DER
- Energy storage is the highest rated emerging technology for the utility to invest in
- Most utilities are seeing minimal or stagnant load growth
- Utilities see grid operations and profitability as the two biggest challenges related to DER
- Utilities do not think grids are secure enough but rate this only sixth in their list of top priorities

The EPRI 2015 Technology Innovation Summit[3] also provided a number of key trends, including the following:

- Tomorrow's grid must be an integrated grid
- The distribution system is where the action is
- Modeling and analysis must become stochastic
- Communications systems are key
- System architecture must evolve to allow customer integration

This last point references the integration of DER and transactive prosumers into grid operations.

[1] JD Taft and A Becker-Dippmann, Grid Architecture, PNNL-24044, January 2015, available online at http://energy.gov/epsa/downloads/grid-architecture
[2] Utility Dive and Siemens, 2016 State of the Electric Utility Survey Results, available online at: http://www.utilitydive.com/library/the-state-of-the-electric-utility-2015/
[3] Hosted by Southern California Edison and Pacific Gas and Electric Company on October 28 and 29 in Huntington Beach, CA.

2.0 Part 2: Architectural Principles and Tools

The definition of Grid Architecture and its antecedents were described in the first Grid Architecture report to the Department of Energy. This report section expounds further on Grid Architecture paradigms and principles and introduces the first of several planned Grid Architecture tools. Finally, a new reference website for Grid Architecture is described.

2.1 Seven Modern Grid Architecture Paradigms

Many paradigms used in grid work during the "smart grid" era in the last decade were derived from enterprise information technology methods. Newer paradigms are needed for grid modernization, since the scope of Grid Architecture is much larger than the IT/OT integration that was the focus of the smart grid work. Figure 2.1 lists a number of key paradigm shifts from the discipline of Grid Architecture that apply in this work and report.

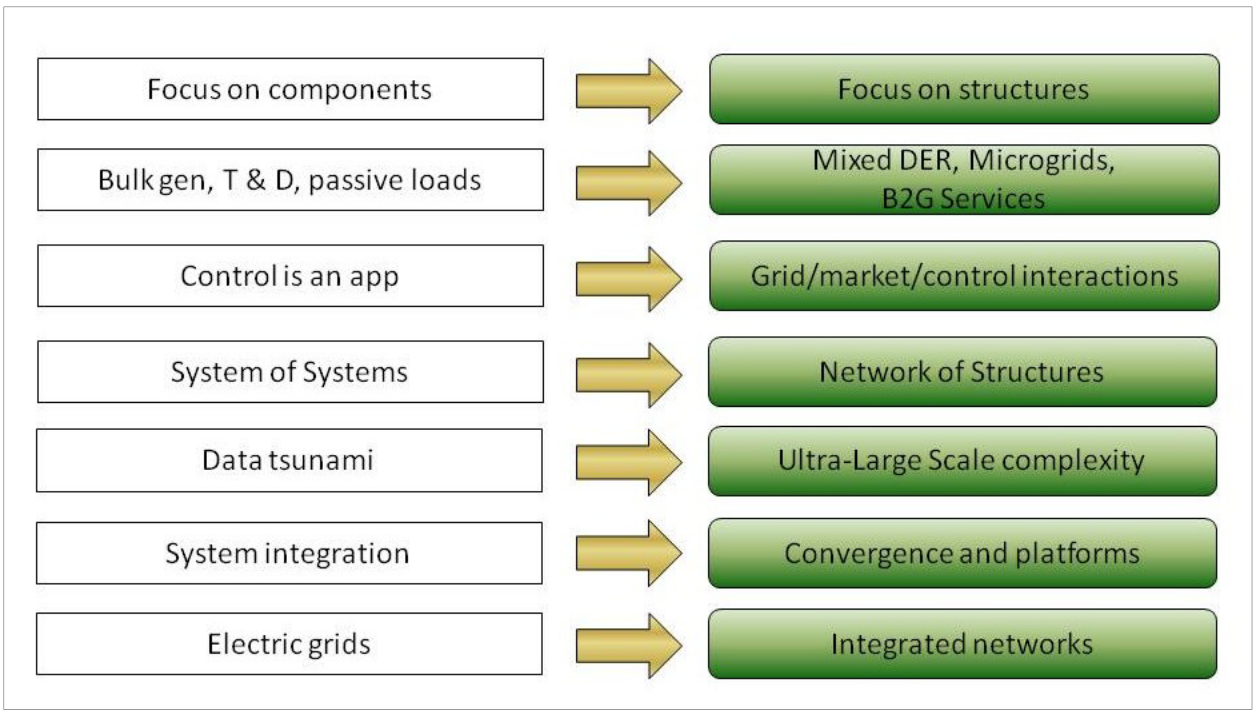

Figure 2.1. Grid Modernization Paradigm Shifts

2.1.1 Brief Descriptions of the New Paradigms

<u>Focus on structures</u> – a basic tenet of system architecture is that structure sets the essential limits that determine ultimate system capabilities. By focusing on structure, legacy constraints can be identified and reduced and new capabilities can be enabled. This is especially true for the grid.

<u>Mixed DER/Microgrids/B2G services</u> – Distribution is no longer a well-behaved set of passive loads. Penetration of DER and the ability of loads, especially buildings, to provide energy and services back to the grid have massive implications for planning, control, coordination, communications, and data management in modernized grids.

Grid/market/control interactions – In the smart grid era, control was viewed as just another application, subject to IT/OT integration along with many other applications, hence the focus on interoperability. For the purposes of grid modernization, Grid Architecture treats control together with markets and physical grids as networked structures and even converged platforms where appropriate.

Network of Structures – In accordance with the focus on structure, the grid is represented as a network of structures. This paradigm is fundamentally more useful in understanding how to enable new capabilities and remove legacy constraints than the System of Systems (SoS) paradigm because it makes cross-domain interactions much easier to identify and manage.

Ultra-Large Scale complexity – Approaches to managing complexity for ordinary systems are inadequate for the grid. A newer paradigm, Ultra-Large Scale Systems complexity, is needed to inform Grid Architecture. Ultra-Large Scale systems are defined by a set of characteristics that were developed for other purposes but match well with grid characteristics.[4] An understanding of these characteristics aids in the development of architectural views for modernized grids.

Convergence and platforms – In the smart grid work, a good deal of focus was on integration but for grid modernization a more important concept is the manner in which networks can converge, thus resulting in new seamless platforms that enable new value streams. Network convergence is discussed in the next section of this document.

Integrated networks – In urban environments, the electric distribution network plays a crucial role but is one of many networks which could operate collaboratively or could even converge. One of the keys to facilitating collaboration or convergence of these networks is the communication network.

> **Architectural Insight 1**
>
> Grid modernization involves much more than IT/OT integration. Further, the essential structure of the grid is changing due to a variety of forces as referenced in Part 1. These and other issues have resulted in the need to employ newer and fundamentally more powerful paradigms for reasoning about and re-structuring the grid than have been used in the past.

2.2 Network Convergence[5]

Customer adoption of distributed energy resources and public policies are driving changes in the uses of the distribution system. A system originally designed and built for one-way energy flows from central generating facilities to end-use customers is now experiencing injections of energy from customers anywhere on the grid and frequent reversals in the direction of energy flow. In response, regulators and utilities are re-thinking the design and operations of the grid to create more open and transactive electric networks. This evolution has the opportunity to unlock significant value for customers and utilities. Alternatively, failure to seize this potential may instead lead to an erosion of value if customers seek to defect and disconnect from the system.[6]

[4] Linda Northrup, et. al., Ultra Large Scale Systems, Carnegie Mellon University, June 2006, available online at www.sei.cmu.edu/library/assets/uls_book20062.pdf

[5] This material is drawn from a paper by P. De Martini and J. Taft, Value Creation Through Integrated Network and Convergence, Feb. 2015, available online at http://smart.caltech.edu/papers/ElectricNetworksConvergence_final_022315.pdf

[6] J. Creyts, et al., The Economics of Grid Defection, Rocky Mountain Institute, Cohn Reznick Think Energy, and HOMER Energy, 2014

Current grid modernization investments may be leveraged to create open networks that increase value through the interaction of intelligent devices on the grid and *prosumerization*[7] of customers. Moreover, even greater value can be realized through the synergistic effects of convergence of multiple networks.

2.2.1 Network Value

Traditional electric distribution systems that deliver energy one-way from central generation to customers have a linear value model. That is to say, the value of a traditional grid is proportional to the sum of the number of customers served. At the current forecasted[8] long-term average growth rate of less than 1%, customer and societal value from the distribution system will not appreciably increase.

In contrast, an electric network that is based on a system of interconnected people and energy producing/consuming devices that are interactive can create significantly more value. These open and interactive networks have a unique property in that increasing the number of points of interactive connectivity results in nonlinear value growth and creation. The conceptual value model put forward by Robert Metcalfe[9] is that the potential value of a network is proportional to the square of the number of connected users of the system (n^2). A classic example is a telecom system in which a two-phone system has a fraction of the network value of a system with a million phones connected, as illustrated in Figure 2.2 below. This concept eventually became known as Metcalfe's Law.

The electric system is also undergoing a transformation in the use of the system by customers. Instead of the historical one-way flow involving customers consuming electricity, an increasing number are also producing electricity. Beginning in the 1980s, customers began to install onsite co-generation plants that often provided services to system operators in addition to supplying a customer's energy needs. Today, the number of distributed resources has exploded into thousands of devices that can provide interactive services and multi-directional flows across the network. This changing use of the electric grid is increasing its network value – but only if it can support n-way power flows and multi-sided transactions. A closed distribution system will not create network value.

[7] Prosumers can both produce and consume energy.

[8] U.S. Energy Information Administration's *Annual Energy Outlook 2014* (AEO2014)

[9] In 2007, Robert Metcalfe described this potential as the "EnerNet" building on his "Metcalfe's Law" that characterizes the exponential value effects of networks such as the Internet, social networking and business.

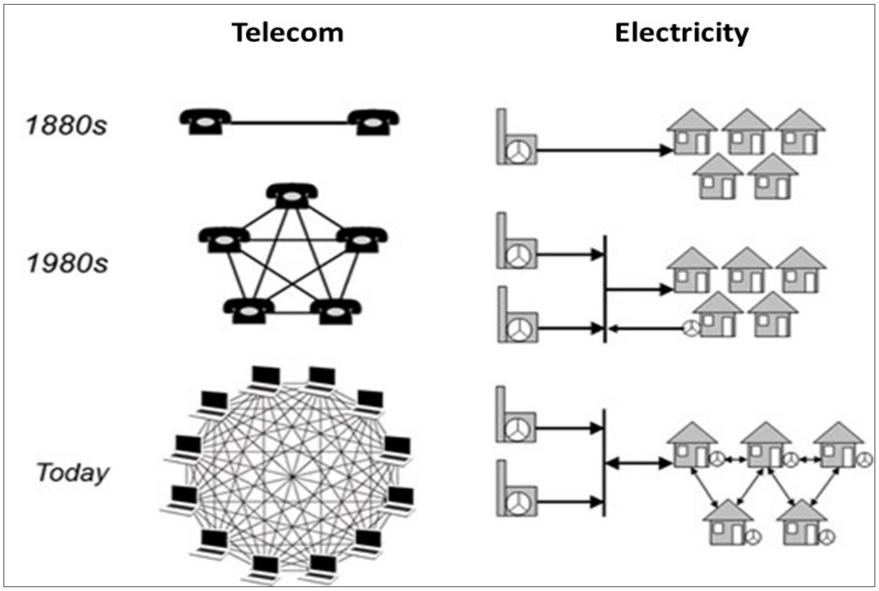

Figure 2.2. Evolution of Telecom & Electric Networks

2.2.2 Integration

An important architectural concept in development of a network is "integration." Integration is an engineering task associated with adding more nodes on a network and realizing the economic value of that addition. This is often undertaken on a case-by-case basis until plug and play interoperability is achieved through standardization. Some examples of integration are an electric utility connecting a wind generation farm to its transmission grid, or connecting a microgrid to its distribution system, or integrating distributed resources into distribution operations. This is a very important and foundational task that is currently underway in the electric industry, highlighted by California's distributed resources planning proceeding and New York's Reforming the Energy Vision (REV) proceeding. When integration reaches a standardized process it can have industry-wide effect and create value based on network effects. It enables optimization across a single network but does not, however, transform related industries.

> **Architectural Insight 2**
>
> System integration is the connection of various components and subsystems so that the resulting overall system can deliver a specified set of capabilities and optimized value.
> Integration is a routine engineering task - valuable, but not inherently transformative.

2.2.3 Platforms

A future with potentially 30% of the US installed resource capacity coming from distributed resources and customer participation requires a different physical distribution system than exists today. Consequently, the role of distribution system operations will expand to the management of thousands and potentially millions of distributed generators, and other energy resources. In short, as a more distributed future unfolds, the distribution utility will naturally become a critical hub between customers' resources and bulk – and potentially even local – power markets. The key will be to create an open network that incorporates a platform designed to enable vast numbers of relatively small transactions. Such a network platform can build on the roughly $20 billion annual grid modernization efforts currently underway by U.S. investor-owned and major municipal utilities. A platform, by one definition, is a set of common elements of form used in more than one product or system. In practice, platforms typically integrate a set of information technology, physical infrastructure, and standardized business processes in an open manner to provide unique services. One type of platform, an open multi-sided transaction platform, is essential to enable network economic value to be realized.

Open multi-sided transaction platforms are designed to enable a variety of transactions among multiple buyers and sellers and to be able to scale in an efficient manner. These platforms usually add complementary revenue models beyond basic transaction services.[10] Examples include shopping and payment platforms, such as eBay and PayPal that in 2014 enabled $20 billion in transactions.[11]

2.2.4 Convergent Value

Convergence of networks is a powerful transformative force that has strong implications for both business and technology. The opportunity to converge two or more networks arises from the potential to integrate various elements of the respective networks or systems in the context of resources sharing and common architecture. This integration of two or more networks into a unified system creates value that is intrinsically synergistic. Convergence leverages the respective nonlinear value properties associated with each network. In simple terms, the combination creates more value than the sum of the discrete networks. Consider two networks of size N_1 and N_2, respectively. The value of the combined network[12] is proportional to $(N_1 + N_2)^2$ which is greater than the simple sum of their values $N_1^2 + N_2^2$ by the amount $2N_1xN_2$. This last term represents the synergistic value from convergence.

Architectural Insight 3

Convergence is the transformation of two or more networks or systems to share resources and interact synergistically via a common and seamless architecture, thus enabling new value streams.

This concept is widely known in the telecommunications industry, which has experienced several convergences. For example, the integration of voice with data, and subsequently the addition of video, has ushered in tremendous innovation and value creation. Virtual medical care would not be possible without the convergence of voice, data, and video in telecommunications. Consequently, convergence is not about one technology being displaced by another – typewriters did not converge with computers and horses did not converge with automobiles, for example.

[10] A. Hagiu, Multi-sided Platforms: From Microfoundations to Design and Expansion Strategies, Harvard Business School, 2006

[11] J. Donahoe, CEO eBay, Interview at Web 2.0 Summit, April 2012

[12] For illustration only, Metcalfe's Law is used to illustrate the conceptual potential. In practice this is unlikely to be achieved exactly and other more complex models may apply with greater accuracy.

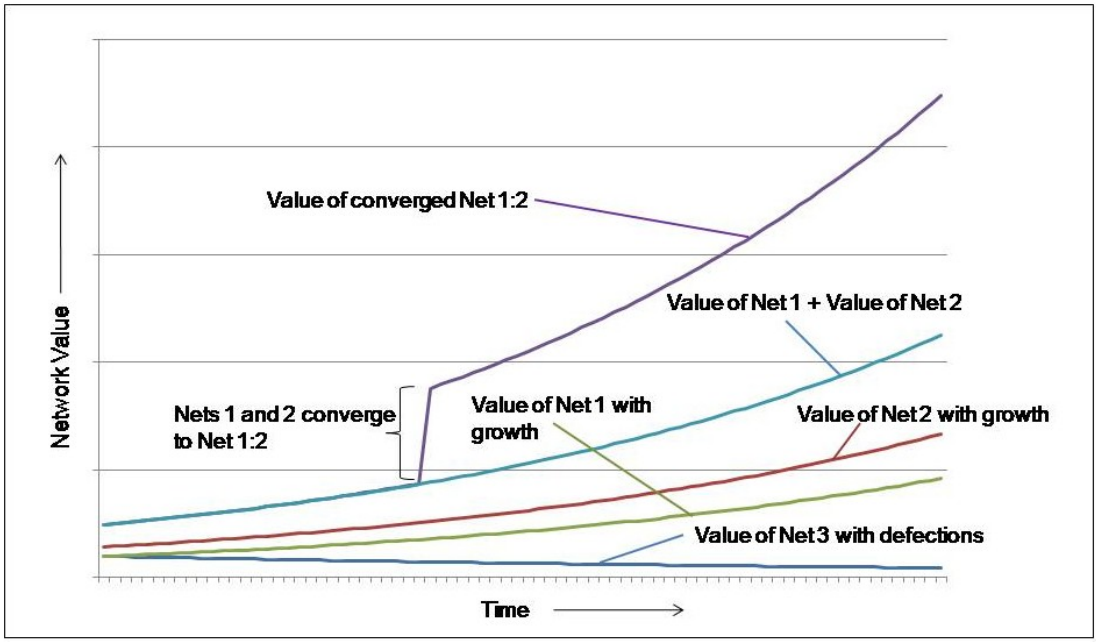

Figure 2.3. Scenarios of Network & Convergent Value

Various scenarios of network and convergent value over time are conceptually illustrated in Figure 2.3. The purple curve represents the converged value of two networks (Net 1:2). The underlying network value growth for each is represented by the red and green curves respectively for Net 2 and Net 1. If two networks are complementary, but do not provide synergistic benefits, the result is the sum of the two networks represented by the aqua color curve Net 1 + Net 2. Net 3 represents the erosion of network value from an increase in the number of network defections as may arise from customers becoming fully energy self-sufficient and going off grid. Of course, not all networks or combinations of networks realize Metcalfe's value potential due to aspects of human behavior that have led to newer models which account for the fact that interactions are not uniform but rather have a long tail distribution.[13] The non-linear nature of convergence will still lead to the same essential synergy effect, namely that the extra synergy component itself grows nonlinearly with the combined size of the converged network. However, an open transactive electric system has significant potential to realize the synergy suggested by Metcalfe's Law, since it is the largest physical network at the core of our modern economy.

Convergence most typically applies to whole industry segments, not just individual companies or customers, and results in significant changes in how products or service are delivered as well as how economic value is created. Convergence is a macro-process that comes about as a result of some imperative, which may be social, economic, political or regulatory. In fact, regulation is one of the larger drivers of convergence, though it may also be an inhibitor. Convergence arises from a recognition that increased value can be achieved through synergy if the two networks can be meshed so that each survives and prospers via the newly created value stream.

[13] Bob Briscoe, Andrew Odlyzko, and Benjamin Tilly make the argument that a better model for actual value realization for communication networks is that value is proportional to n log(n); see "Metcalfe's Law is Wrong", IEEE Spectrum, July 2006, pp.34-39.

2.2.5 Value Evolution

The future of the electric system and its potential value is under discussion in several US states and internationally. These industry discussions have generally defined four potential futures for the distribution grid based on changes in the use of the electric system stemming from customer adoption and utility procurement of distributed energy resources.[14] The four end-states in Figure 2.4 should be viewed as being on a continuum in terms of the potential value of the grid.

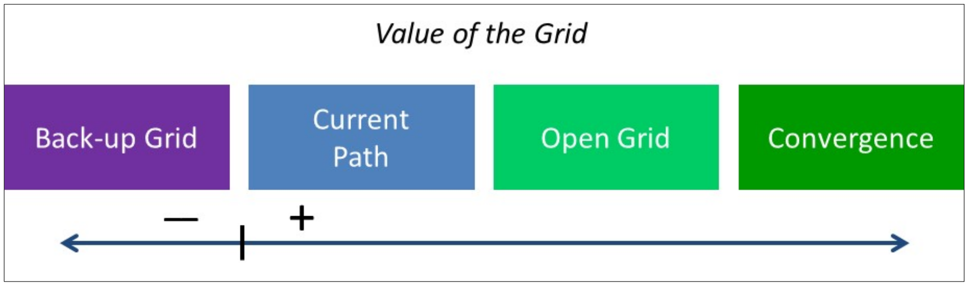

Figure 2.4. Value of the Grid Continuum

2.2.6 Current Path

This pathway is based on traditional unidirectional use of the distribution system by customers and others focused on investments to replace aging infrastructure, integration of advanced technologies to improve reliability, resiliency, safety and efficiency. The Current Path reflects the current grid modernization underway and establishes a value "baseline," but takes little or no account of the potential consequences of distributed energy resource proliferation.

2.2.7 Back-up Grid

This end-state envisions a smaller number of customers remaining wholly dependent on the integrated electric system and a growing number of former customers that have become totally self-sufficient and have disconnected. A Back-up Grid provides less societal value than the Current Path and may lead to further erosion through a "death spiral"[15] of increasing rates driven by fewer customers sharing the cost of the system, which then incentivizes more customers to become self-sufficient and defect.

2.2.8 Open Grid

This end-state builds on the current grid modernization investments along with an evolution of distribution system designs to create an open, plug-and-play grid to enable seamless integration of diverse distributed energy resources and independent microgrids into a unified multi-layered optimization structure. This enables the creation of substantial new network value.

Electric grid evolution as defined in California, Hawaii, and New York involves transitioning from a closed single purpose system to a more open, flexible, efficient, and resilient network that integrates distributed energy resources into the operation of the distribution and bulk power systems. Technology

[14] P. De Martini, *More than Smart: A Framework to make the Distribution Grid More Open, Efficient and Resilient*, Caltech and Greentech Leadership Group, 2014

[15] P. Kind, *Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business*, Edison Electric Institute, 2013

investments, as described by the Electric Power Research Institute,[16] combined with an evolution of distribution engineering designs can create such an open-access distribution platform. A networked grid would involve "node-friendly" standardized, low cost physical and information interconnections.[17] This approach would also allow for the continued evolution into a multi-cellular structure comprised of microgrids as discussed in a 2014 California Public Utility Commission (CPUC) staff microgrid report.[18] These changes should be evaluated in the context of the potential to realize the value of open networks as demonstrated in other industries.

2.2.9 Electric Network Convergence

The value of the Open Grid achieves greater value through convergence of an integrated electric network with other networks such as water, natural gas, and transportation systems to create more efficient and resilient infrastructure. This enables economic and environmental policy objectives for synergistic customer and societal benefits. The following discussion highlights several aspects of emerging convergence for the electric system.

2.2.10 Grid Convergence

The convergence of the electric network with cyber, social, and economic networks illustrated in Figure 2.5 has created what is has been called the smart grid. Each of these four classes of networks has been integrating with electric system for nearly 20 years. The difference is that a more transaction-oriented distribution system is beginning to emerge which allows the value of convergence to develop. The convergence of the grid with information and communication networks has been underway for quite some time, and received a boost during the "smart grid" phase of grid evolution in the last decade. It continues with the focus on grid modernization and not only brings its own value streams, but also comprises a part of the platform for enabling other convergences.

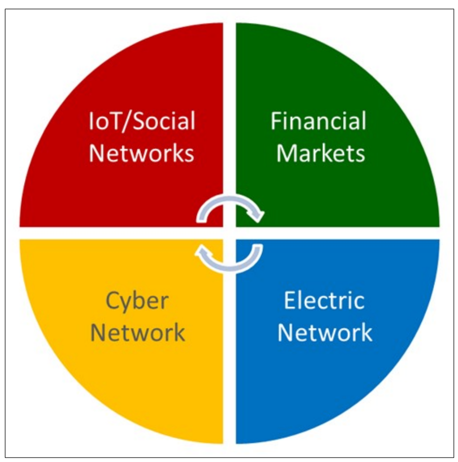

Figure 2.5. Four Class Network Convergence

The creation of markets that began with the industry restructuring in the 1990s has continued, with markets and market-like mechanisms either implemented or proposed for ever deeper penetration into the

[16] EPRI, *Needed: A Grid Operating System to Facilitate Grid Transformation*, 2011

[17] J. Raab, "Proposed Changes to the Uniform Standards for Interconnecting Distributed Generation", 2012

[18] C. Villareal, D. Erickson, M. Zafar, Microgrids: A Regulatory Perspective, CPUC Policy & Planning Division, 2014

grid. While not all parts of the US have access to bulk energy markets, there have been recent expansions of the markets to include various ancillary services and market mechanisms to foster integration of utility-scale renewable generation into the grid. Considerable work is now being done on how to monetize a variety of potential services at the distribution level, including consideration of what could amount to distributed markets to support integration of large amounts of distributed generation, energy storage and demand response.

Since social networks have become ubiquitous, it is not surprising that utilities would turn to them to provide new ways to interact with their customers. Some utilities have encouraged customers to interact with each other via social media to support and reinforce energy conservation practices. Perhaps most interestingly, there are indications of the spontaneous formation of informal "markets" trading in "comfort" (really building energy usage) in commercial office buildings and operating via social networks.

2.2.11 Natural Gas and Electric Convergence

The perception of natural gas as the less damaging fossil fuel for central and distributed generation is creating a convergence that has profound implications on the US electric system. Also known is the fact that gas production, processing and delivery to electric generation uses electricity at many points in the chain. Early stage convergence drives tighter coupling of networks (gas and electric in this case), so when activities like harmonization of markets and cross-observability implementation begin to occur, combined with the structural interconnection noted above, the convergence becomes a possibility. Ultimately, late stage convergence can result in the formation of new value streams, and while this does not appear to be happening yet, it is worth being aware of the possibility so that convergence is not unnecessarily hampered and innovation can occur. SeeFigure 2.6 below for an illustration of gas-electric physical interconnection.

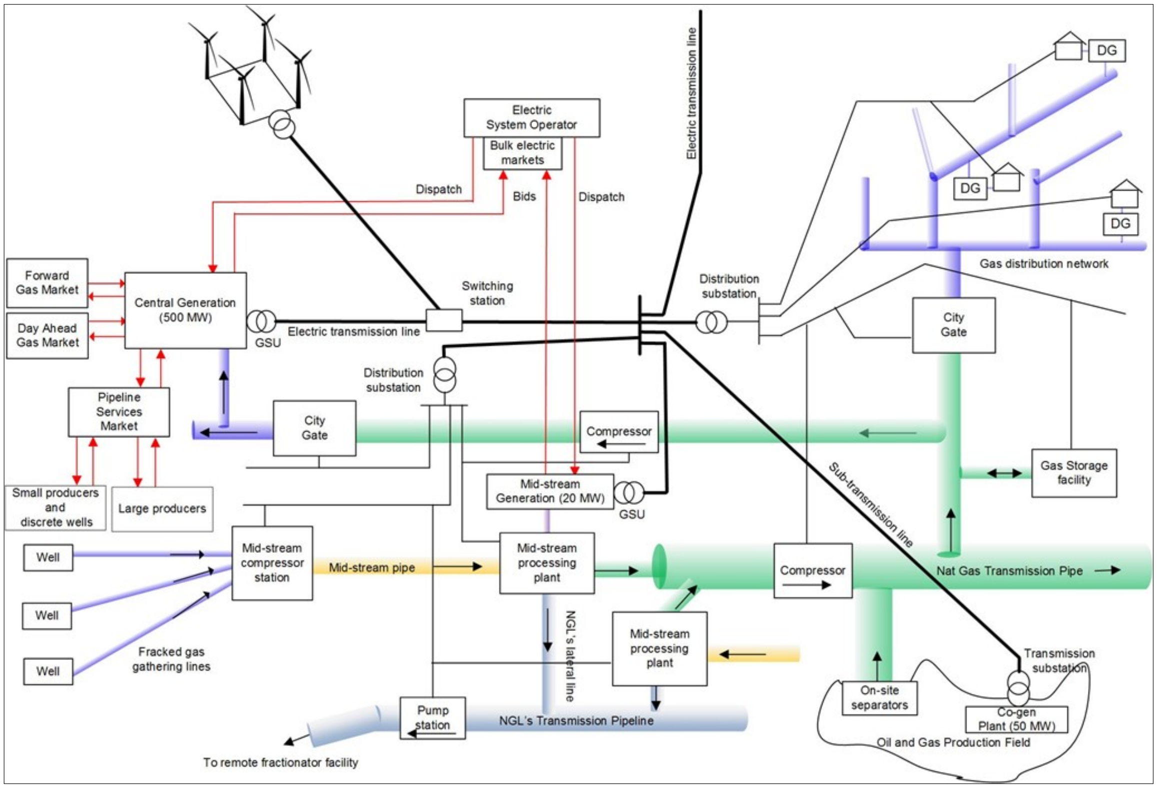

Figure 2.6. Natural Gas and Electric Systems Convergence

2.2.12 Water and Energy Nexus

Likewise, the nexus of water and electrification of transportation represent another opportunity to create synergistic value. In particular, California's Water/Energy Nexus proceeding is focused on developing a partnership framework between investor owned energy utilities and the water sector to realize the value of convergence of water and electric networks. The energy embedded in water includes the amount of energy that is used to collect, convey, treat, and distribute water to end users. Also, this includes the amount of energy that is used to collect and transport wastewater for treatment prior to safe discharge of the effluent. The opportunity is significant as water represents 19% of energy consumption in California as identified in Figure 2.7.

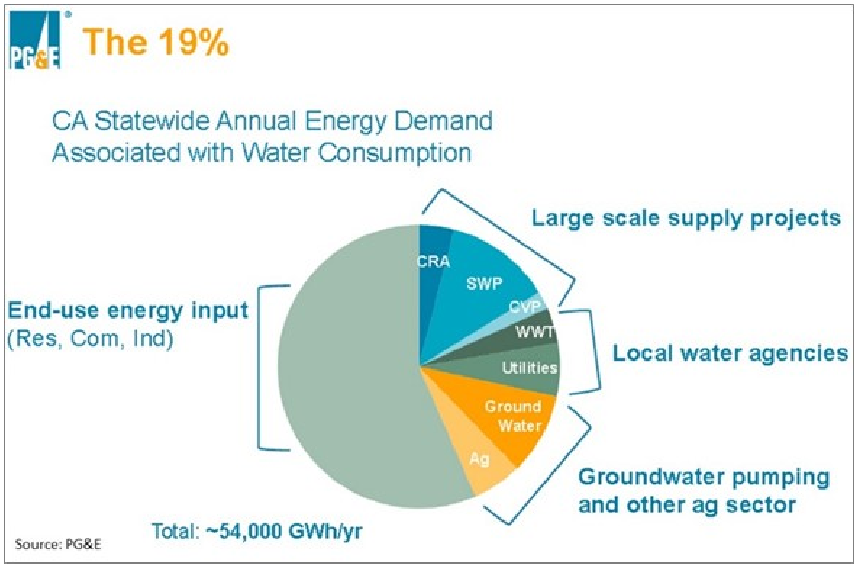

Figure 2.7. California Water System Energy Consumption

Persistent drought conditions also mean the need for conservation of water has become a critical issue. This presents the opportunity to explore the synergies to accomplish both a reduction in energy use and related greenhouse gas benefits, better optimization of electric grid assets and efficiency, and importantly the conservation of precious water. Water systems are "naturals" for converged operations because they have large aggregate demand over many sites, each with sizable discretionary loads. This creates opportunities for:

- Diverse efficiency measures
- Excellent Demand Response performance
- Leveraging onsite hydro, distributed generation, and energy storage capabilities
- Utilizing existing water SCADA systems for integrated controls

Open long-distance transport of water, as is common in California, offers an opportunity to reduce evaporative water losses by siting solar photovoltaic generation over major canals,[19] thus increasing the amount of large-scale solar on the grid without the adverse impacts of siting on pristine desert lands.

Additionally, as suggested by SolarCity,[20] desalination of ocean water may prove to be a long-term drought-mitigation solution, and could also offer an effective use of excess energy from solar PV as identified in the CAISO's "duck curve" analysis.[21]

2.2.13 Evolution of Electric Network Convergences

For the power grid, multiple convergences have occurred and continue to occur at differing paces and times. Information and Communications Technology (ICT) was an early convergence for transmission and then distribution, with aspects of this convergence still progressing, especially at the distribution level. Moving forward in time, we see additional convergences involving transmission, but significantly

[19] The Canal Solar Power Project in Gujarat, India is an example.

[20] Public comments by Peter Rive, COO SolarCity at More Than Smart Conference, September 2014

[21] http://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

more for distribution, largely due to consumer interactions and the push toward greater use of distributed energy resources. Figure 2.8 illustrates a rough sequence of convergences, although it should be noted that convergence does not necessarily happen uniformly across the industry. Some convergences are long-tail processes, and the sequence of convergence going forward may be altered by legislation or regulation as well as market forces.

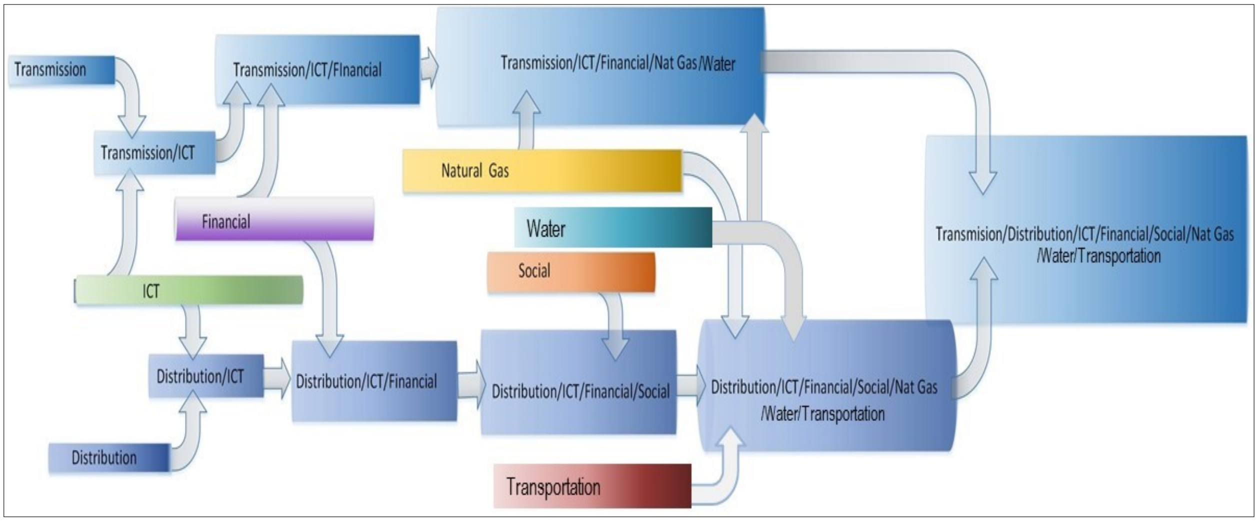

Figure 2.8. Evolution of Several Convergences with the Electric Grid

2.2.14 Architecture

Convergence of networks has tremendous value, but questions do arise as to whether it is possible to architect convergence and whether is it possible to recognize when convergence is beginning. To address these concerns it is necessary to apply system architectural methods. One of the functions of system architecture is to specify (allocate) the interfaces among system components. Doing so from a whole-system perspective rather than in a bottom-up fashion provides the context that assures proper interface design and later, standards specification. This approach also offers a better ability to manage emergent system behavior as well as to define platforms for convergence.

A system architectural approach considers the form and function as well as behavioral aspects of a system.

- *Form* is a set of components and structure (relationships among components), where components are connected by interfaces; form is the thing that executes function.
- *Function* is comprised of an operand[22] and a process.

As elements of form are bought together, new functions arise. Form aggregates in a sort of linear way, but function does not. Some of these system behaviors are deliberately sought as the product of methodical design activity. This is what gives systems their power: the system functionality can be greater than the sum of the parts' functionalities, due to the nonlinear combination effect.

Systems may also have unanticipated behaviors, commonly called emergent behavior. Emergence is a phenomenon whereby unanticipated behavior arises from the interconnection of components into a form and where no subset of the components exhibits this behavior. Emergent behaviors may turn out to be

[22] An operand is the object or entity on which a function is performed.

desirable in retrospect, or they may be undesirable. When systems are designed "top down," emergent behavior may be planned to some extent, although it also may occur in unforeseen ways as well. This is especially true in ultra-large-scale systems like power grids. When systems are designed or just built "bottom-up," behavior emerges as the form is constructed and planning the emergent behavior is essentially impossible.

If convergence occurs in an ad hoc fashion, then the combinations of form and function are being created in a more or less bottom-up fashion and so emergence is essentially impossible to predict. A net result of this is that it may be difficult or impossible to recognize an opportunity and develop a suitable convergence platform until after the fact of the converged system's evolution.

Alternatively, if we wish to enable convergence platform formation as a means to facilitate or stimulate convergences with the power grid, and new value streams, we should recognize that the discipline of Grid Architecture can address these issues in a way that bottom-up component and system integration cannot. Specifically, a well thought out grid architecture can enhance the formation of convergence platforms by reducing structural impediments to secure information exchange and control coordination, enabling scalability of functions and interactions with new endpoints, and providing the means to manage complexity.

2.2.15 Convergent Integration

The implications of convergence include the need for physical and information integration, but they also extend further. Convergence with the electric system also requires integration at the control systems and business process levels. Control system integration is important because this is where the processes are *operationalized*; lack of control system integration prevents the value chain from operating properly, or at least impedes it significantly. Given the emerging trends in power grid operation it is clear that the existing controls were designed in ways that were right for the requirements of the time, but are now not adequate going forward.

Coupling of the networks involved in a convergence can also be a matter of degree. Given that coupling must occur on multiple levels, it can be the case that not all levels are so equally or deeply meshed. Consequently, we sometimes find convergences that have left some aspects of integration undone or only lightly done until additional developments in terms of markets or regulation drive further meshing. An example would be convergence of commercial buildings and electric networks. There is a very minor degree of integration presently, but building and electric grid control systems are not well integrated, so there is no common control architecture.

Coupling of networks is not just a technical integration issue. Each network has an inherent "time clock" or pace at which certain processes execute. When these time clocks do not match well, then a certain amount of "mesh friction" occurs, and that impedes full realization of the expected synergies and thereby limits complete realization of the potential value stream. An example would be the natural gas/electric grid convergence, where the markets operate at different paces, as do the related transport mechanisms and control systems.

2.2.16 Value Chains versus Value Networks

Another consideration is value creation and value flows across a network. Conventionally, value flows "downstream", in a sense following the flow of a product or service delivery process. In a more distributed energy future, this view may not be sufficiently sophisticated for the network and convergence issues for the electric grid. Traditional linear value chains are giving way to nonlinear value networks and in the context of the modern grid, services in particular may flow at least bi-directionally (and may flow N-directionally), just as electric power and grid information may flow. Consequently, the question of what is downstream may need to be replaced with a more nuanced view of value creation and flow.

Business value creation in the emerging 21st century electric industry will be largely derived from two fundamental models:

- Value Network: Profit based on collective value of a partner ecosystem. Revenues from direct sale of services, and secondary and tertiary revenues including revenue sharing and after-sale services. This requires a dominant position in a value network. Examples: Cisco and Wal-Mart
- Switchboard: Intermediary based business enabling exchange (including delivery) of information, money, goods and services between multiple buyers and sellers in an open and massively scalable manner. Examples: Amazon, eBay/PayPal, and ICE

Businesses today depend on a set of relationships that include customers, technology and other suppliers, and alliances/partnerships with firms that have complementary products/services. The resulting ecosystem of relationships is called a value network. These networks allow firms to expand their services and augment products in ways that increase customer value and the firm's profitability. The relationships need to be complementary to work – that is, mutually beneficial. This has been more challenging when viewed in the narrow confines of a single value chain, like sales of kilowatt hours of electricity, where the relationships operate in a zero-sum game. The opportunity today is to consider commercial relationships in emerging electric networks and related convergence.

Additionally, the creation of open electric network platforms as discussed in New York to "animate markets" is the same as creating a switchboard that enables market transactions among various parties. In a more distributed context this may involve managing the physical flows and financial transactions among millions of resources and parties.[23]

Benefit accrual in the utility industry is complex and value often accrues in places in a value network other than where investment is to be made.[24] Consider the potential interaction between commercial buildings and electric grids as an example. In the past, a grid operator (or a load serving entity or LSE) would view buildings as downstream "loads" and building operators would view the grid as providing a service (we even call it electric service). In a converged environment, grids and buildings would exchange energy-related services, so some value would flow to the buildings, but some value would flow from the buildings back to the LSEs and the grid, and potentially through them to other grid entities such as regional grid operators. In addition, buildings may be able to generate services for other buildings or loads in a Local Energy Network or microgrid environment, so that value streams may be rather complex, rendering the concept of "downstream" dependent on point of view, if not entirely irrelevant.

Every good business has at least one strategic control point. That is, a point where influence can be exerted over the use of a value network or between converged networks to gain competitive advantage and improve profitability. Identifying strategic control points is much less clear as customers have increasing influence over more complex and increasingly virtual value networks. For example, Google established a control point with online search to "control" valuable information for advertisers. Google extended its control with its Android smart phone operating system that reached 70.1% market share in Q4 2012 compared to Apple's 20.1%, according to the International Data Corporation (IDC). Within 15

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[23] L. Kristov and P. De Martini, 21st Century Electric Distribution System Operations, CAISO and Caltech Resnick Institute, 2014, available online at: http://resnick.caltech.edu/docs/21st.pdf

[24] P. De Martini and L. von Prellwitz, Gridonomics™, Cisco, 2011, available online at: http://www.cisco.com/web/strategy/docs/energy/gridonomics_white_paper.pdf

years, many utilities may lose control of their profitability in the context of the historical value chain to customers and others due to advancements in technology and distributed resources. This is why utilities need to reconsider the value of existing strategic control points and those that will emerge as electricity networks and convergence opportunities evolve.

In a growing number of states, the scale of DER adoption is creating significant pressure for fundamental changes in the design, operation, structure, and regulation of the electric industry already reaching critical mass and policy action is underway. In particular, a grid is sought that provides safe, reliable, and efficient electric services by integrating distributed energy resources to meet customers' and society's evolving needs while being aligned with the wholesale market and bulk power system. Central to these discussions is the evolution of the electric distribution system into an open network that may also converge with other critical infrastructure to enable customer value and public policy objectives.

Architectural Insight 4

At the grid architectural level, it is much more useful to consider network convergence than just integration, especially in the context of the network-of-structures model of the grid. Identification of potential resulting value streams and the platforms that enable them can provide much stronger justifications for investment in grid modernization than simple integration can.

2.3 Flow Models

Flow models are used in a variety of technical fields, including data architecture and database design, genetics, network design, operations research, traffic analysis, and software design. Flow models take many forms, appropriate to the specific problem domain involved. Here we develop demand/supply flow models for electric power grids as a means to discover an architectural insight about Distribution System Operator (DSO) roles and responsibilities. The following diagrams employ a set of acronyms defined here:

- DER – Distributed Energy Resources
- DO – Distribution Operator (Distribution Provider)
- ISO – Independent System Operator
- TO –Transmission Operator
- DG –Distributed Generation
- DS –Distributed Storage
- DR –Demand Response
- EE –Energy Efficiency
- VER –Variable Energy Resources
- BES –Bulk Energy System

Figure 2.9 shows a basic grid flow model for a system with invokable demand response and behind the meter DER-based net load reduction. Red arrows show demand flow and blue arrows show supply flow. The numbers in the diagram illustrate magnitudes in normalized form so that balances can be seen.

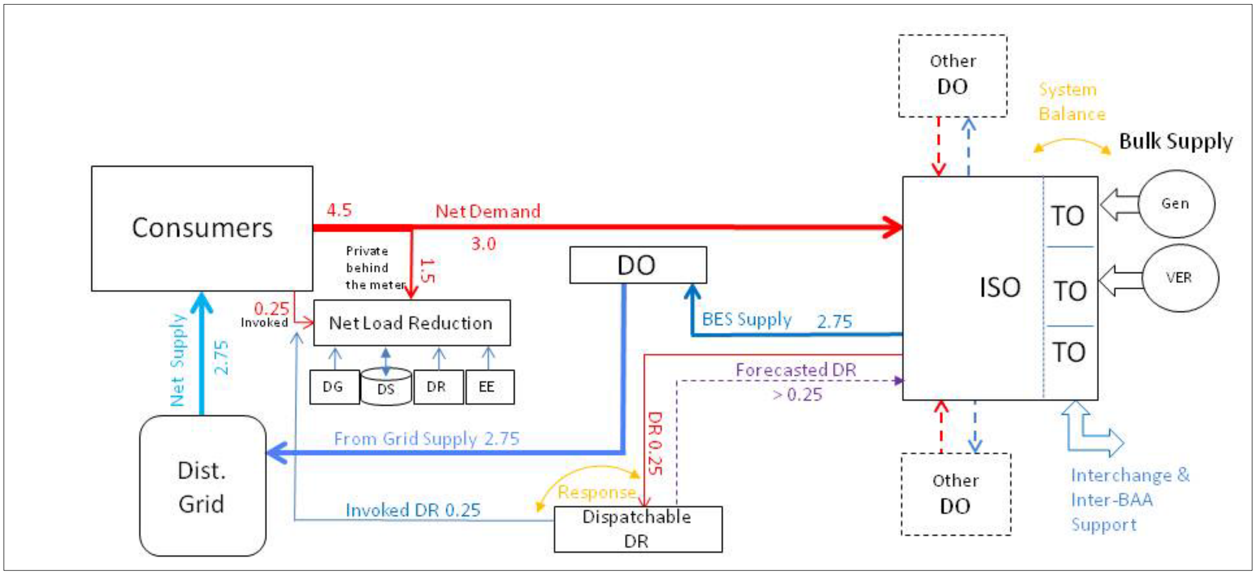

Figure 2.9. Basic Demand/Supply Flow Model

Note that demand originates from the consumers and drives the entire system. Demand "flow" is an abstract concept and is not strictly the same as power flow. Demand flow may be instantiated through load activation or through information exchange (as in the case of forecasted demand). Supply flow is an abstraction which may be communicated through actual power flow, or through information flow (as in the case of forecasted DR capacity).

In Figure 2.10 DER has been added to the flow model. DER is dispatched from the ISO market level, thereby bypassing the DO. This model also includes storage at the bulk system level, the distribution grid level, and in prosumer and merchant DER form.

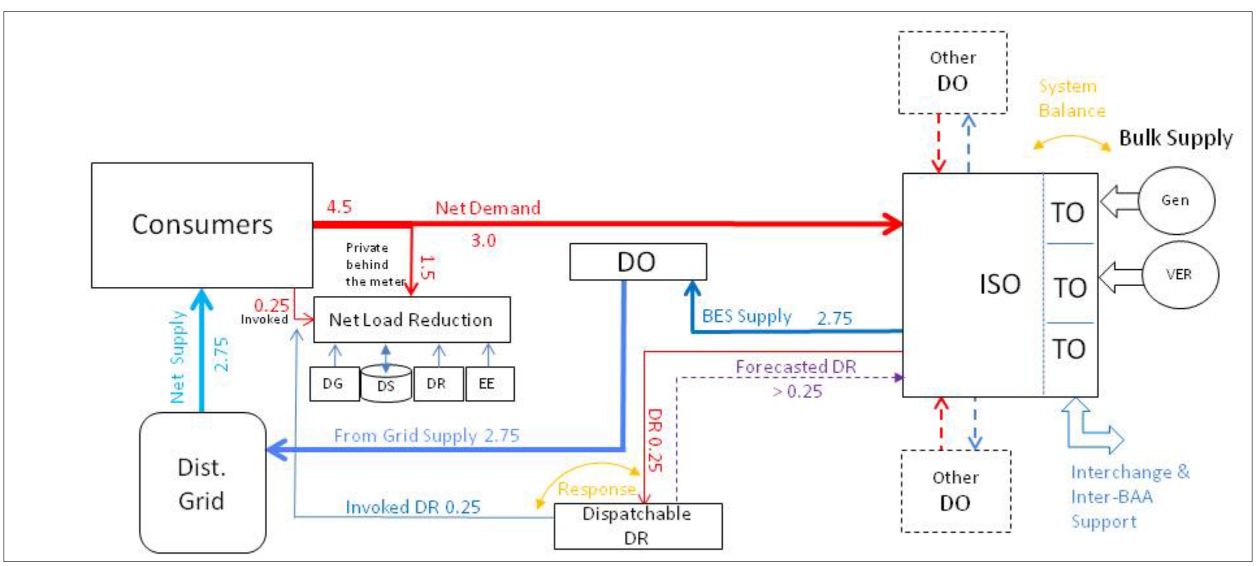

Figure 2.10. Flow Model with DER

In Figure 2.11, the DO has been converted to have DSO functionality, with the responsibility to coordinate energy assets in its distribution service area in accordance with agreements negotiated between the ISO and the DSO for energy exchanges and services at the boundary Transmission/Distribution substation (or equivalently, the relevant Locational Marginal Pricing node).

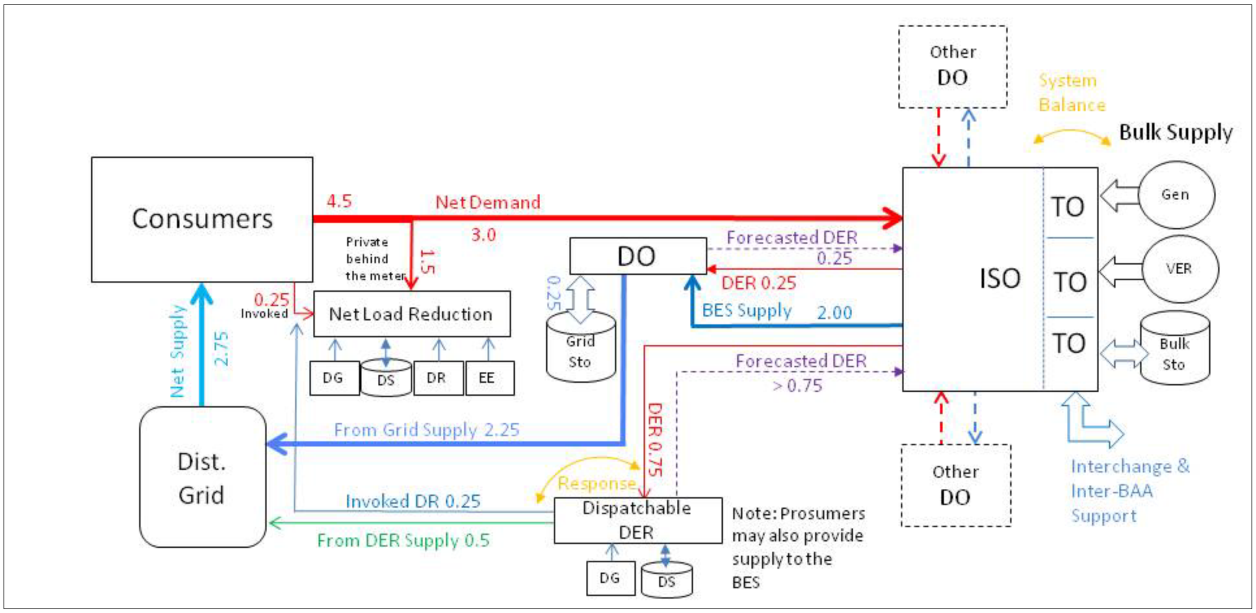

Figure 2.11. DSO-based Flow Model

Note that in this model the ISO/DO bypassing issue has been eliminated. The ISO does not require visibility into any of the assets at the distribution level since the DSO manages these assets to meet the agreement with the ISO at the interface point. The DSO plays a central role between the ISO and the consumers and DER, allowing the ISO to concentrate on managing the bulk energy assets for balance across the set of DSOs/DOs.

To get to the essential architectural insight, is simplified to the form shown in Figure 2.12.

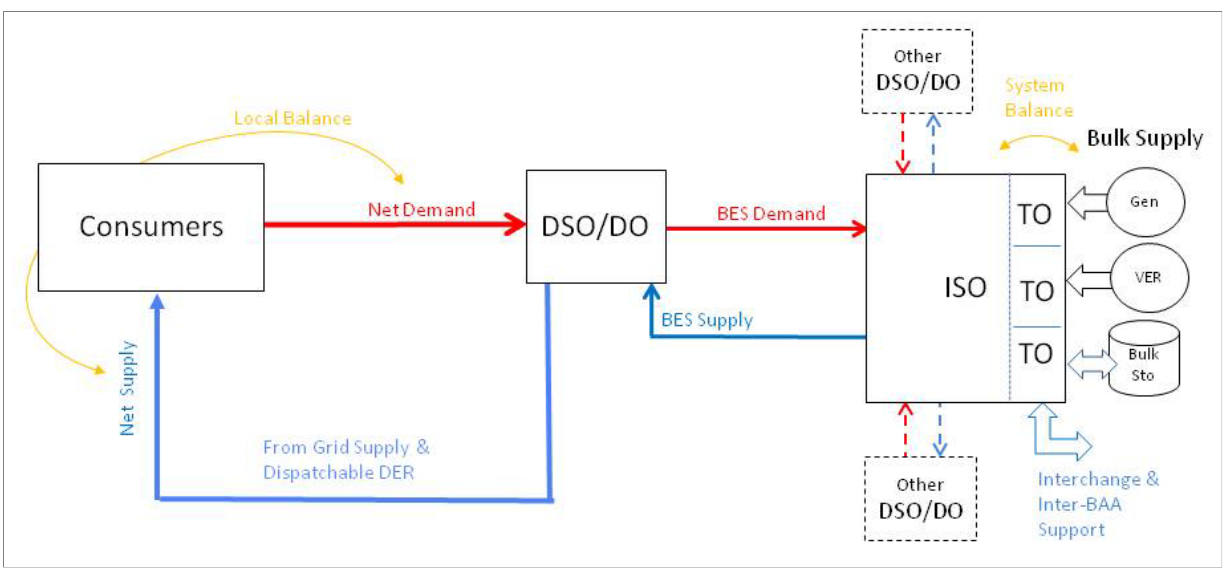

Figure 2.12. Simplified DSO Flow Model

Recognizing that the overall system is driven by the consumers, the DSO is at the nexus at two loops, but is not the middle layer of a hierarchical control as might ordinarily be assumed and is the case for many versions of third party DR and DER aggregation energy services organizations.

In this form, the two primary loops are evident: the BES/ISO-to-DSO/DO loop where system balance is maintained (by the ISO) and the DSO/Consumer/DER loop, where local balance is managed (by the DSO). In this form the implied control structure is revealed, as is the central role of the DSO in grid operations.

> **Architectural Insight 5**
>
> In the total DSO model, the ISO (or RTO) can properly be viewed as providing an energy service to multiple DSO/DO nodes. The DSOs coordinate multiple resources, including the dispatchable DER assets and BES energy and services as needed (and may provide energy and services back to the BES). The ISO and BES are in effect an energy "cloud" and the ISO is the energy cloud service provider for DOs.

2.4 Industry Structure Diagram Browser Tool

One of the issues that the first Grid Architecture report reviews highlighted was the need for ways to make some of the more complex diagrams consumable by non-technical users who are not system architects but are grid stakeholders. Many of the tools typically used by system architects are difficult to master and are not generally accessible by the average person. This work has created a first version of a web-based tool for browsing industry structure diagrams, which are multi-layer diagrams of high complexity that document and illustrate the relationships among the many entities involved in a power grid.

The industry structure browser has been created to be run from an ordinary web browser and so can be accessed via the internet. It provides a way to show individual layers of the structure diagram, as selected by the user. Mousing over a box in the diagram provides drilldown information on that entity class represented by the box; mousing over a relationship line does the same and also highlights the entire line throughout the diagram to all its endpoints. Figure 2.13 below is a screen shot of the industry structure browser tool.

This is the first of a suite of planned grid architecture tools. In addition to extending this tool to other diagram types, tools will be developed for architecture mapping, evaluation, and mathematical optimization, as well as tools for architecture validation, observability strategy development, and co-simulation.

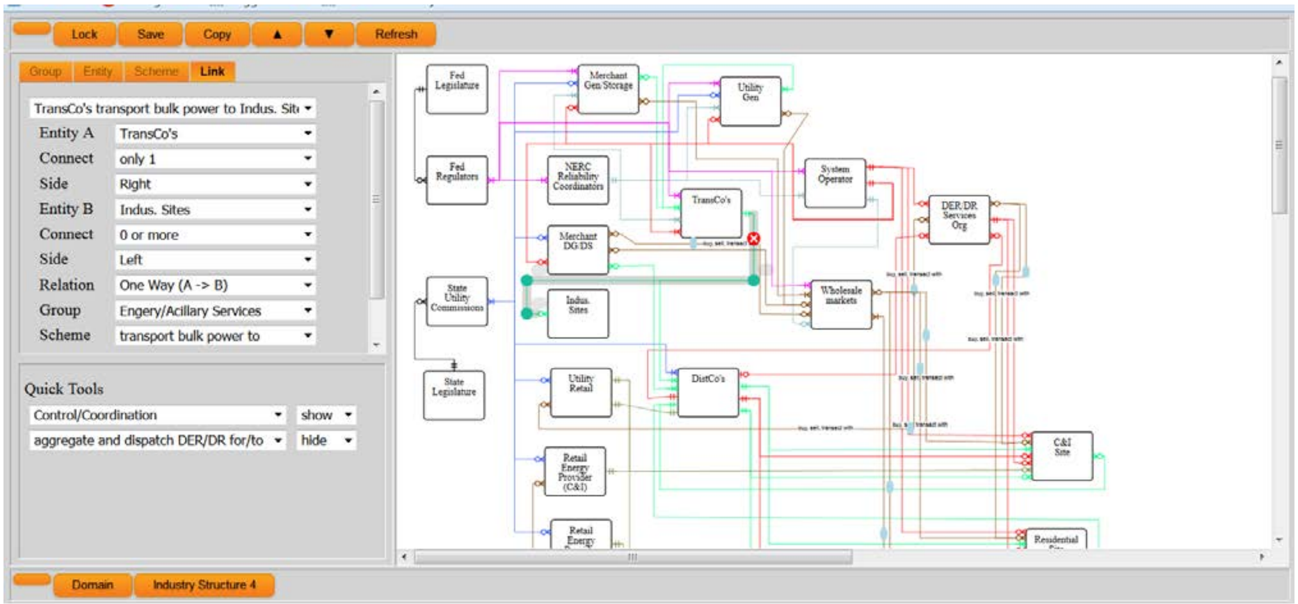

Figure 2.13. Screen Capture for Industry Structure Browsing Tool

2.5 Grid Architecture Website

PNNL has created a website to act as a reference resource for Grid Architecture. It contains extensive background material as well as documentation of advanced concepts. It presently contains or references over a thousand pages of relevant material. The website is organized into five web pages:

- Home page – introduction to Grid Architecture, explanation of the need for Grid Architecture
- Basic Definitions page – terminology used in Grid Architecture
- Advanced Concepts page – deeper dives into complex Grid Architecture views and topics
- Methods page – explanations of Grid Architecture processes
- White Papers page – reference materials from internal and external sources

Screen shots from these pages are shown in Appendix C. The website can be accessed at web address http://gridarchitecture.pnnl.gov/ starting in February 2016. As additional Grid Architecture developments are documented, new postings will be added to the website.

2.6 Architectural Qualities and Properties and the Relationship to Metrics

2.6.1 Background

Understanding how grid architectural elements affect the ability of the grid to meet consumer needs is closely related to understanding the performance of the grid itself, in either existing or proposed future forms. While there is a long history of using a rather wide and in some areas very deep set of performance measures, these measures have mostly been developed in an incremental and ad hoc fashion. Those measures will not disappear, but for the purposes of developing new grid architectures, it is necessary to develop the set of grid qualities and properties and associated performance measures together. Such a development enables powerful methods of evaluating proposed grid architectural options. Combined with the proper tools to handle the mathematics and provide ways for stakeholders to explore alternatives, it has the side benefit of making grid qualities and properties and their impacts on grid architecture accessible to general grid stakeholders. The methods described here are an outgrowth of a method used to evaluate costs and benefits for smart grid projects in the decade of the 2000's. The original method made use of a three level network: an input layer of functions, a middle layer of outcomes, and output layer of benefits (or costs – the method can and has been used both ways). The purpose of using the three-layer model was to clearly separate outcomes from benefits (or costs) and to make assumptions about each visible. In previous work, outcomes and benefits were frequently mislabeled and mixed, causing confusion in the analysis.

Figure 2.14 below shows an example of a three-layer diagram for benefit analysis. The flow is from left to right; to make this quantitative each arrow is assigned a value. The value can be a contribution percentage or an actual monetary or other value. For example, the arrows in the grid function to outcome portion can be monetary values of the functions, and the arrows from outcomes to benefits can be relative contribution fractions. Costs can be handled in the same fashion. It takes considerable systems analysis to determine the numerical quantities, but once this is done, the three-layer diagram provides a structure in which they are combined, analyzed, and applied. The coloring of the lines in the diagram is for visual clarity only; on the left they group the lines coming from any particular function whereas on the right they group the lines leading to any particular benefit. In this method, the line values were developed for a specific time horizon (such as one year). Once this diagram was built, traditional spreadsheets were used to do the investment analysis, using the three-layer diagram as a guide. Even without the spreadsheet, such a diagram was helpful in communicating and analyzing the relative importance of various actual or potential grid functions.

Such a three-layer graph also provides a framework for developing a set of performance measures. The benefits layer yields performance measures that focus on customer impact, whereas the outcomes layer yields performance measures that focus on operational effectiveness. The arrows are the mappings from functions to outcomes to benefits; by developing the mappings, it becomes much easier to ensure completeness and to prevent overlap and entanglement of performance measures than if one tried to map directly from functions to benefits. However, not much rigor was applied to the selection of design of the performance measures, so the method still suffered from some pitfalls.

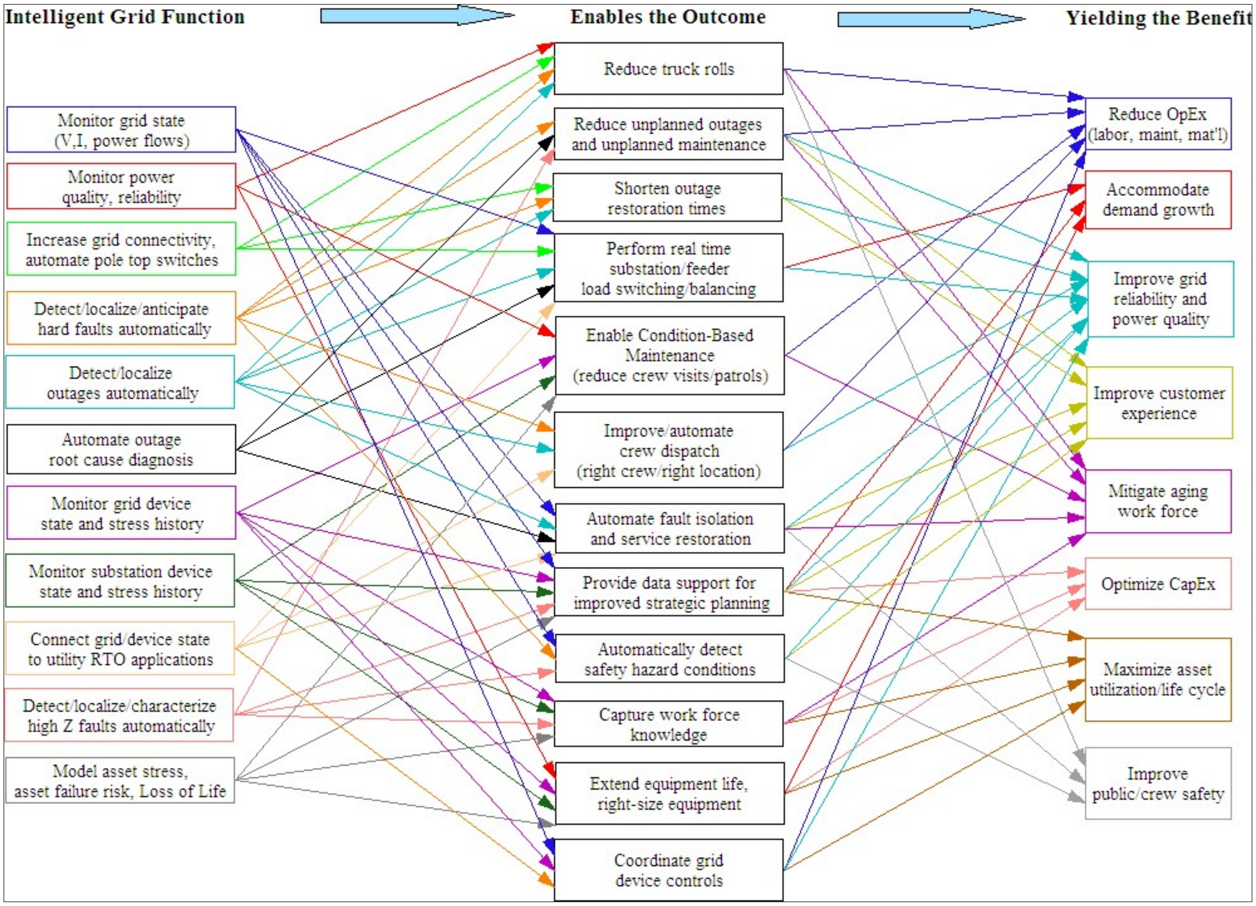

Figure 2.14. Example Three Layer Benefits Analysis Diagram

This method was developed for evaluating smart grid projects at the single utility level and was helpful for that purpose, but is not sufficient for the larger purpose and scope of Grid Architecture. These methods must be extended to be able to answer key questions about grid architectures such as:

- What is the effect of any given architectural element or set of elements on the value of the architecture?
- How can competing architectures be quantitatively compared?

The three-layer method above can be extended using graph theory and matrix methods to provide an analytical means to answer the above questions in an open and objective manner. By applying a degree of mathematical rigor to the definition and mapping of the layers and associated performance measures, the creation of a strong set of qualities, properties, and metrics for the grid can be achieved. The remainder of this paper describes an approach to the specification and use of qualities, properties, and performance measures for grid architecture.

2.6.2 System Properties and Qualities

Important to get the issue of qualities and properties (collectively, characteristics) right because failing that task causes subsequent problems that do not surface immediately:

- Confusion between internal and external characteristics and therefore confusion about who the characteristic serves
- Undetected misalignment of grid performance measures with stakeholder intent
- Confusion among stakeholders about how or even whether their requirements and constraints are being addressed by the grid or a proposed grid architecture
- Incomplete coverage of grid behavior and operational issues
- Impaired ability to determine how well the grid realizes the desired characteristics, due to use of performance measures that entangle multiple qualities or properties

The incomplete coverage issue is important because it causes optimization of some aspects the expense of the ones not being measured.

That last item is in part why performance measures are so important: properly constructed they serve to define the system characteristics in a rigorous manner.

2.6.2.1 System Qualities

System qualities are desired characteristics of the system as seen by end users and other stakeholders with "outsider" perspectives. Think of them as high level requirements which may be expressed qualitatively or quantitatively. Generally, the number of qualities selected for a system is small, and one of the challenges is to choose a set that is comprehensive in nature despite the limited number.

2.6.2.2 System Properties

System properties are characteristics of the system as a whole as seen by "insiders" that combine to provide the system qualities or enable them to be manifest. System properties result from system components and structures, each of which has its own set of properties. Figure 2.15 illustrates an analysis point of view of these relationships. In practice, a complex system will have a large number of desired properties.

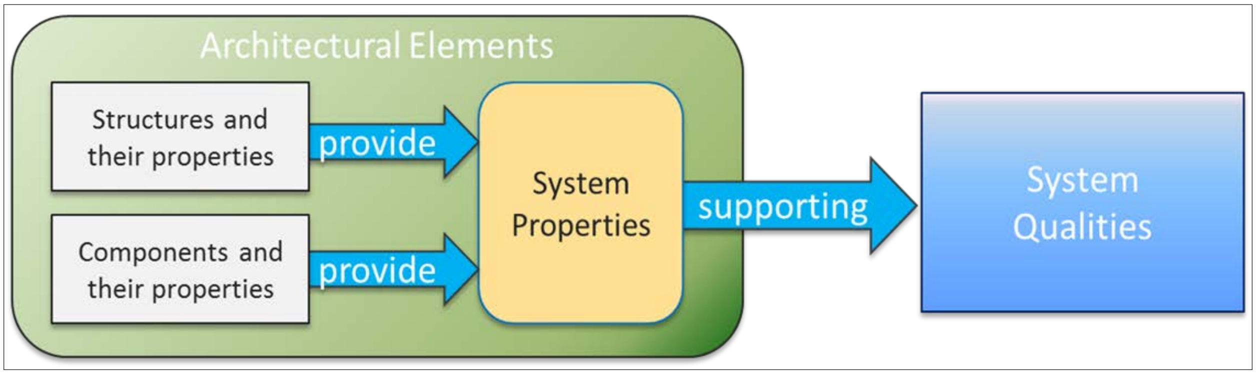

Figure 2.15. Analytical View of System Properties and Qualities

2.6.3 The "ilities" Issue

There has been much recent attention on "ilities" – words ending in "ility" that are presumed to identify key desired characteristics of the grid. The "ilities" are well known in the field of system architecture.

John Doyle of CalTech has compiled a list of such words, although not all of them actually end in ”ility’. They are however used a great deal in attempting to describe useful or desired characteristics or behavior of a system. A list of such words includes:

Accessibility, accountability, accurate, adaptability, affordability, auditability, autonomy, availability, credibility, process capability, compatibility, composability, configurability, correctness provability, customizable, debugability, degradability, determinability, demonstrability, dependability, deployability, discoverability, distributability, durability, effectiveness, efficiency, evolvability, extensibility, failure transparency, fault tolerance, fidelity, flexibility, inspectability, installability, integrity, interchangeability, interoperability, learnability, maintainability, manageability, mobility, modifiability, modularity, nomadicity, operability, orthogonality, portability, precision, predictability, producibility, provability, recoverability, relevancy, reliability, repeatability, reproducibility, resiliency, responsiveness, reusability, robustness, safety, scalability, seamlessness, self-sustainability, serviceability, supportability, securability, simplicity, stability, standards compliancy, survivability, sustainability, tailorability, testability, timeliness, traceability, ubiquitousness, understandability, upgradability, usability

Figure 2.16 below shows an example of an “ility”-based list of desired grid characteristics.

Some issues with this set of terms are:

- No mathematical definitions
- Small set focused on selected topics only
- Mixture of types: some are internal view and some are external but none are defined as such
- No indication of how to deal with grid elements that may contribute to or improve one characteristic while degrading another (example: improve flexibility but degrade robustness or security)

Note that in this list, the topic of security is not shown, despite its importance in the utility world. This is because security was defined to be part of Robustness. Also, note that reliability and resilience were defined as “sub-characteristics” of robustness.

It is important to note that it is not necessary to limit properties to the “ility” list – in fact it is not even desirable to do so for the grid. Some properties may be functional characterizations, e.g., “provides complete power state observability.” In fact, some “ility” words are so general as to be very difficult to define rigorously and therefore are actually not very usable because they lead to more confusion.

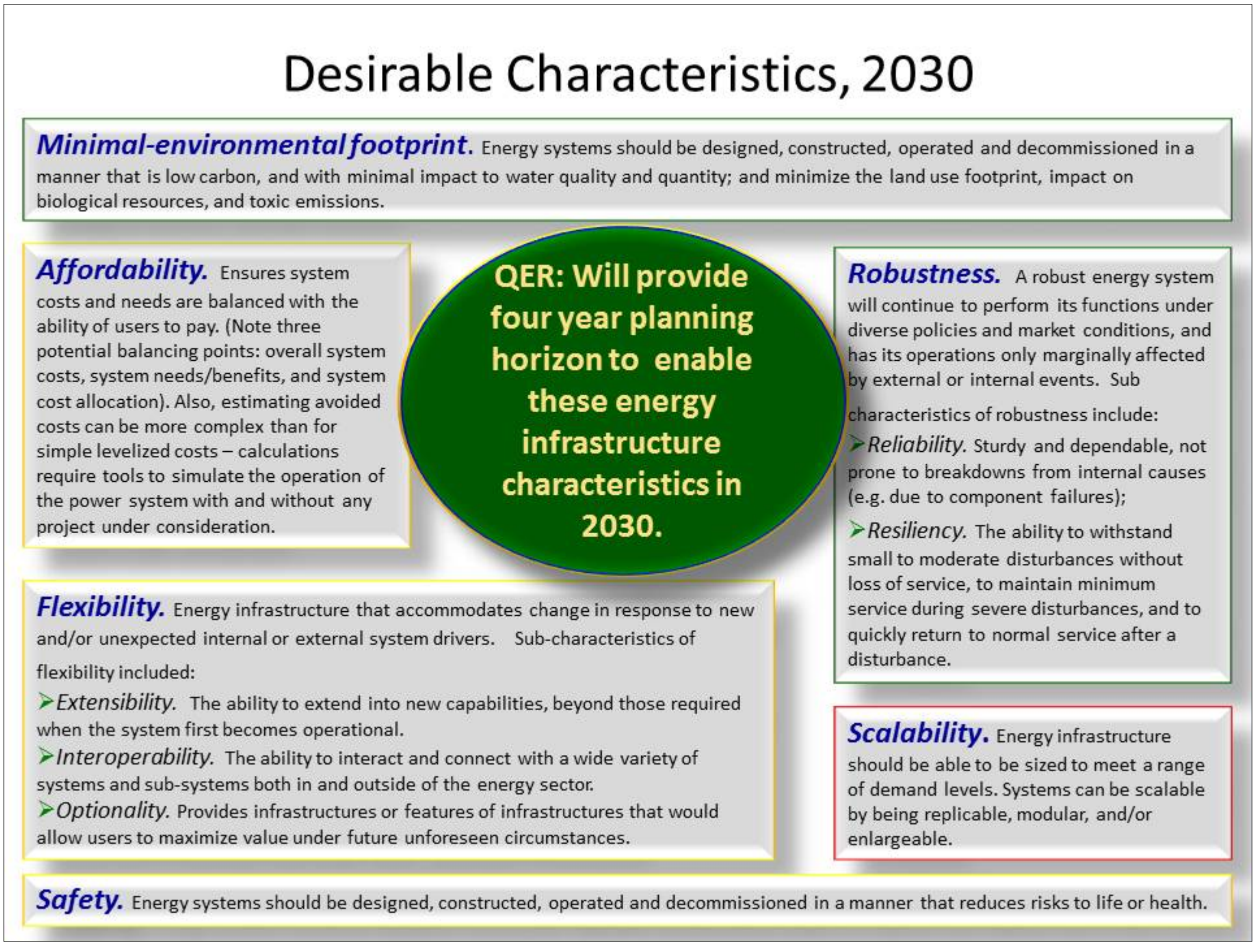

Figure 2.16. Example Set of Desired Grid "ilities"

The characteristics in Figure 2.16 were chosen to highlight specific issues and were useful for the questions being considered. In the more general case of grid architecture, it is necessary to find a set of qualities and properties that address not only these important issues but the full range of operational, economic, environmental, and social issues facing the electric utility industry.

2.6.4 Synthesis of System Qualities and Properties

We start by clarifying the difference between Qualities and Properties of the grid:

- System Qualities represent the consumer viewpoint (users of the system)
- System Properties represent the provider viewpoint (developers, builders, and operators of the system)

Each of these will become a layer in the three-layer model, with the Qualities being the right-hand-most layer, the Properties becoming the middle layer, and the elements of the grid forming the third (left-hand-most) layer. For purposes of grid architecture, we want all of these items to be accessible. Figure 2.17 shows the synthesis view of the relationships.

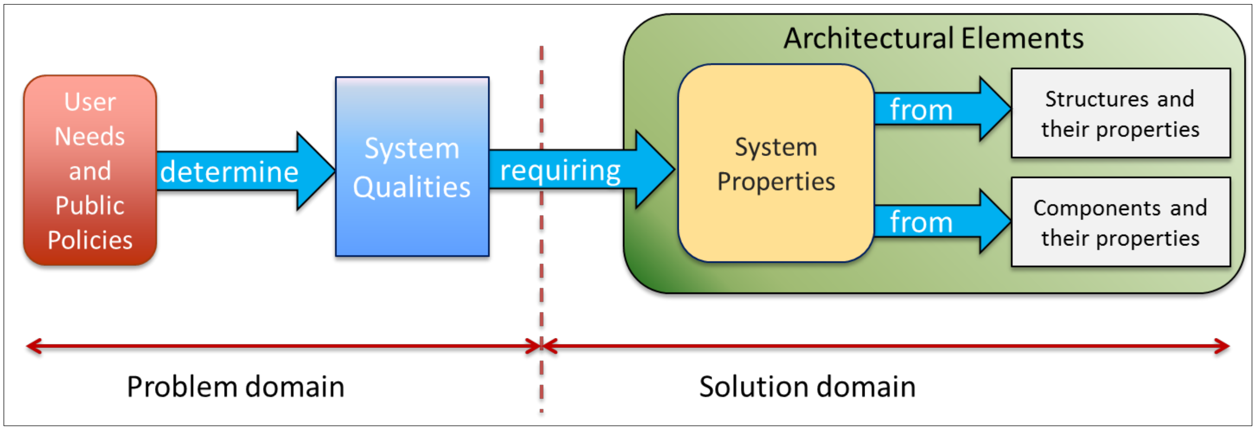

Figure 2.17. Synthesis View of Properties and Qualities

We may view System Qualities as being requirements in the problem domain and System Properties as being elements of the solution domain. It is important to separate Qualities and Properties because mixing them leads to eventual confusion about how well an architecture meets the intent of the various stakeholders, who have differing points of view, differing requirements, and differing constraints. This confusion becomes reflected in the specification of performance measures and ultimately negatively impacts the realization of the value of grid modernization investments.

2.6.5 Requirements for Grid Qualities and Properties

Grid Qualities and Properties should have the following key characteristics:

- Qualities reflect an *external* view of grid behavior; Properties reflect an internal view
- Completeness: must span entire set of grid functions and responsibilities, not just hot button issues
- Must be as nearly non-overlapping as possible
- Must have formal definitions to eliminate ambiguity caused by use of English words with non-technical, vague, or multiple meanings
- Must provide enough granularity to support non-trivial representations and analyses

It is generally recognized that quality set should have a characteristic variously described as:

- Independent
- Non-overlapping
- Decoupled

Well-selected quality sets that have this characteristic simplify the identification of dependency/overlapping/coupling in architectures. Mathematically, we want the qualities in a set to be as nearly mutually orthogonal as possible, suggesting that advanced mathematical concepts are needed. This also greatly aids in performing analytical architecture.

2.6.6 Mapping Properties and Qualities

Once the Quality and Property sets are specified, a mapping can be created between the Properties and the Qualities. This mapping takes the form of a two-layer graph. The graph is then extended to add the third layer on the left, consisting of architectural elements. Figure 2.18 below shows an example of such a two-layer graph that uses a very small set of Qualities and a set of Properties that include very few “ilities.” In this old case, some of the “ilities” were used as Qualities, but this is not recommended as it leads to internal/external view confusion.

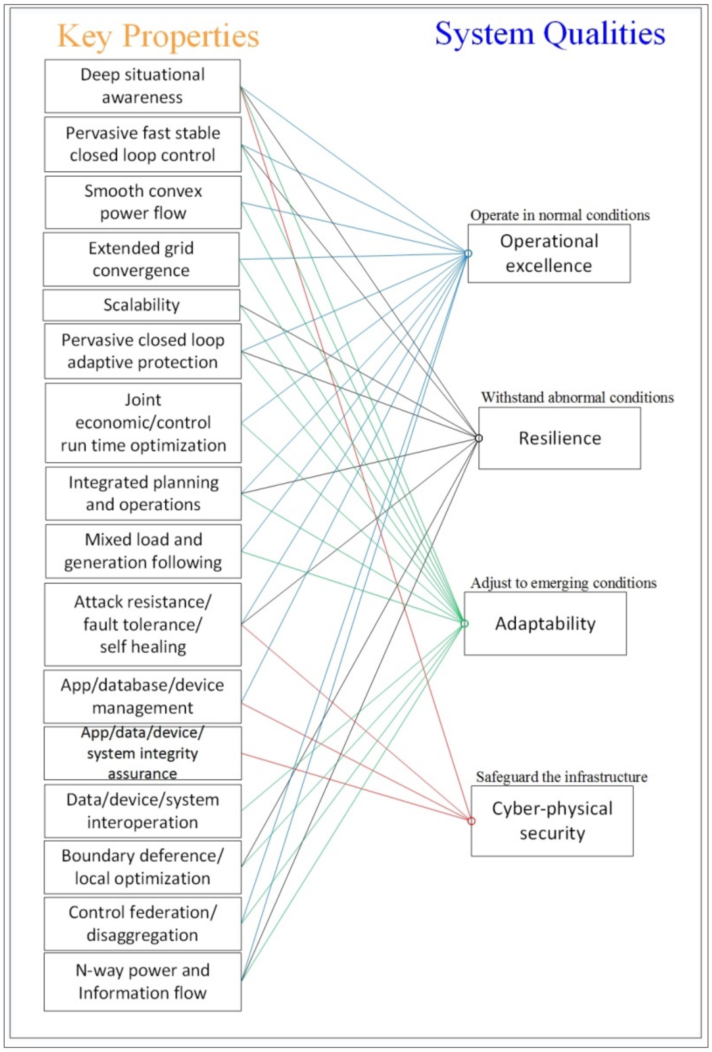

Figure 2.18. Example Property/Quality Mapping

As an aid to ensuring completeness of the Quality set, it is helpful to extend the graph on the right to map to the functions of the utility or utilities involved. Figure 2.19 below shows an example of such a mapping. In this example, the utility functions have been further expanded to the right to show component elements of various functions.

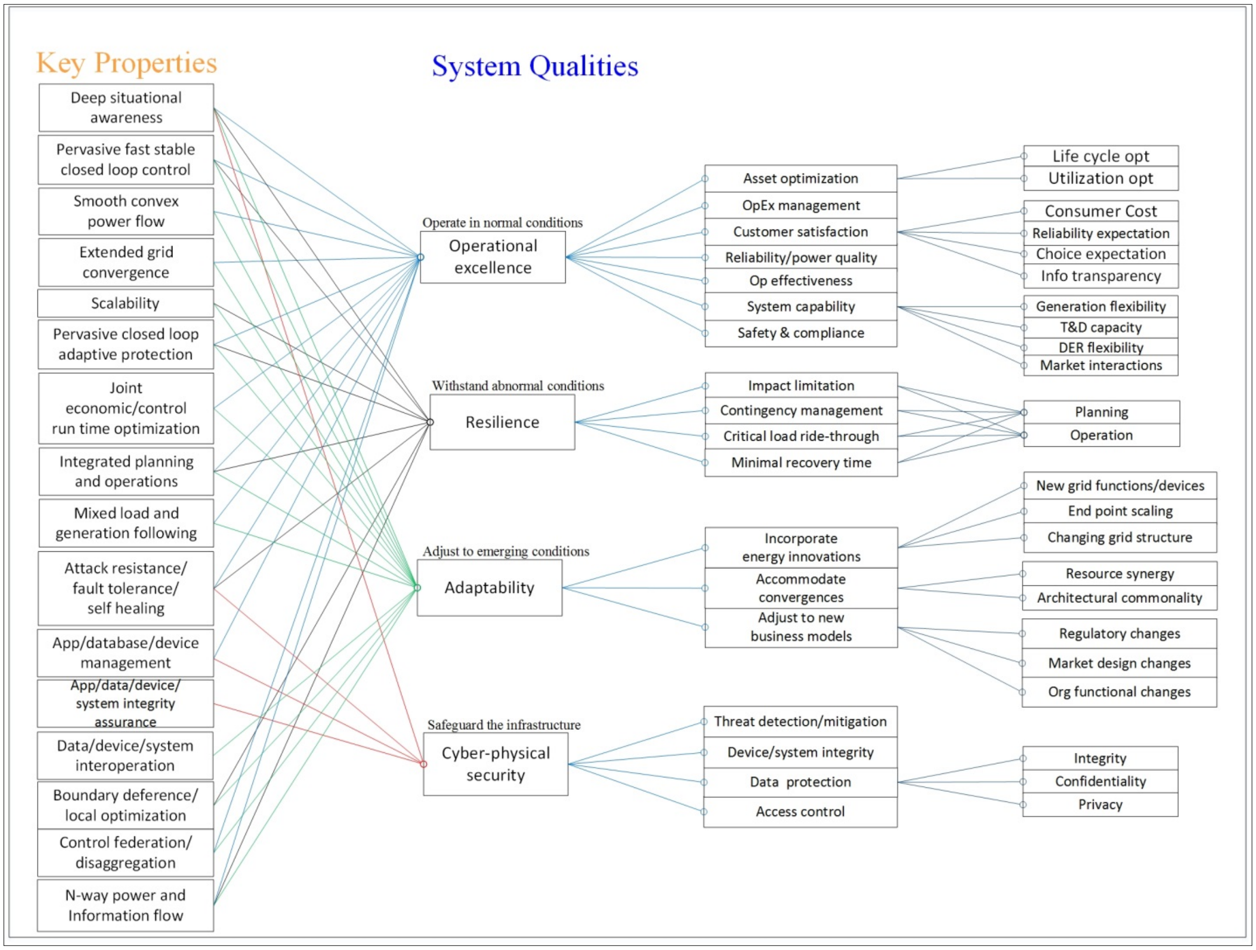

Figure 2.19. Expansion of Mappings to Show Utility Functions

Architectural elements are put into a layer on the left and then mapped to the Properties layer. Due to the large number of elements usually encountered in grid architecture, it is not practical to put them all into a single diagram. Figure 2.20 shows an example of architectural elements adding to the mapping, using key components. In this diagram, selected grid components have been mapped to the Properties, and the components have been further decomposed to the left to show elements of the component classes. The mapping for the full set of grid components is clearly quite large, so it can be useful to use component classes instead of components. Component classes are definitions of component types having a unique set of characteristics common to the members of the component class. The issue in choosing component classes is to avoid over-abstraction that causes a loss of visibility to important Properties.

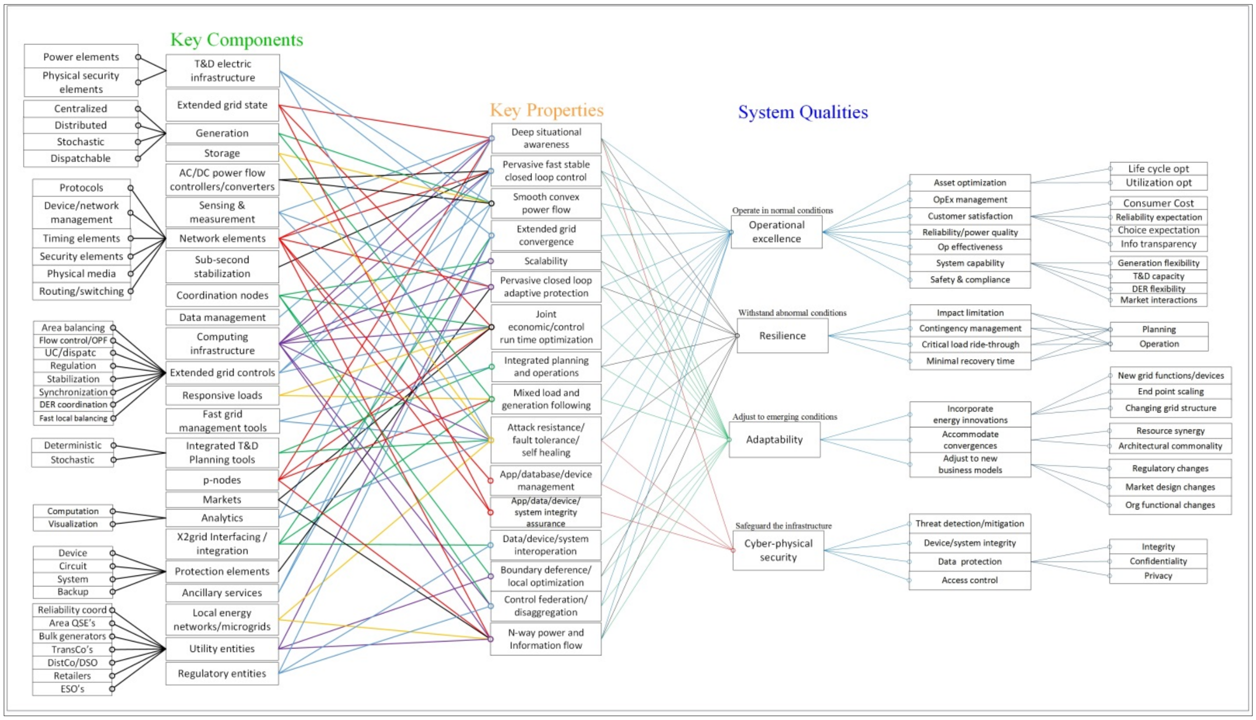

Figure 2.20. Addition of Key Components to Mapping with Expansions

The same type of mapping can and should be done for architectural *structures*, as illustrated in Figure 2.21 below.

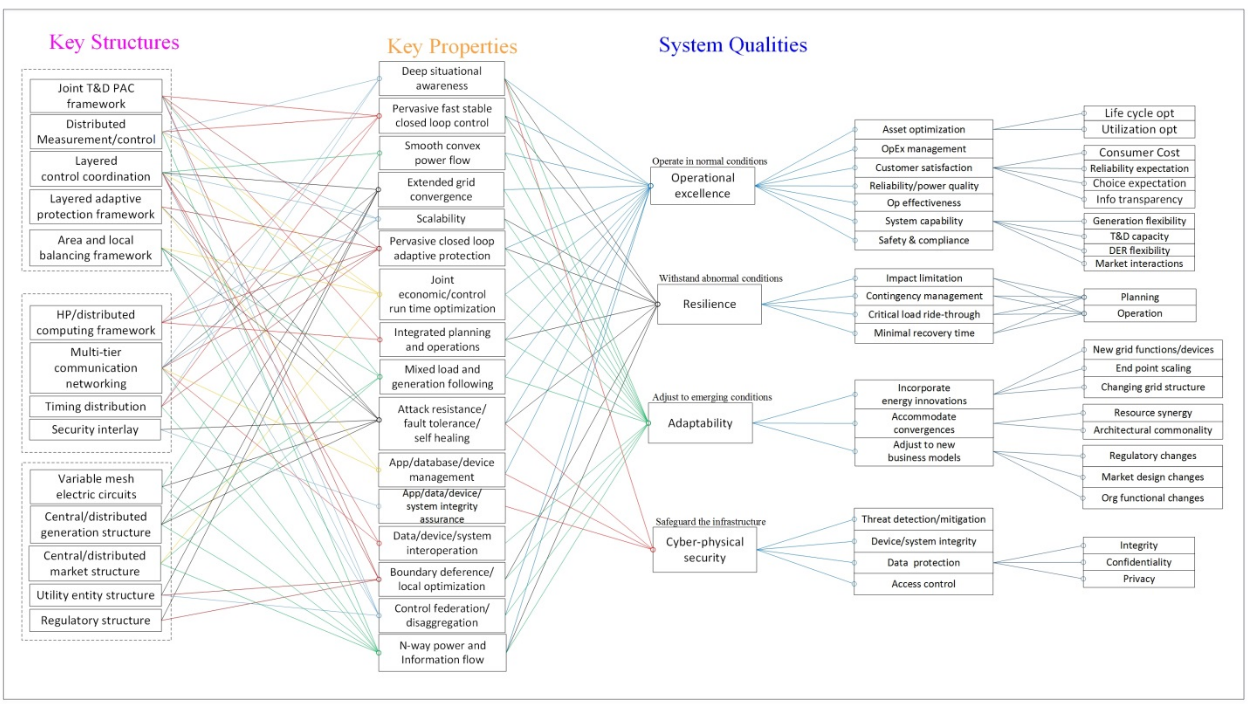

Figure 2.21. Example Mapping of Structures

As mentioned earlier, the mapping lines from architectural elements to Properties and from Properties to Qualities must have values assigned to support analysis. The development of these values requires a great deal of systems analysis.

Once the values are assigned, the tripartite elements-properties-qualities graph may be converted to matrices and the resultant matrix equation may be augmented with additional matrix terms that take into account how some architectural elements contribute or add to specific properties but may actually detract from other properties or qualities. The full definition of the matrix equations is beyond the scope of this document, but the basis for them is shown in the original Grid Architecture report.

2.6.7 System Performance Measures

This paper has used the term system performance measures to avoid the use of the word metrics until this point. Performance measures, often called key performance indicators in the business analytics world, are data-driven mathematical formulae that are intended to provide insights into various aspects of the operation of complex systems. As such, they require measurements of operating data and may be defined as backward-looking or predictive (forward-looking).

Common problems with performance measures include ambiguous definition, definition of something that can be easily measured as opposed to something that is actually informative, and incomplete sets of measures, leading to optimization of some aspects of system performance at the expense of others not measured.

2.6.8 Metrics and Norms

Common terminology for performance measures is “metrics.” This is an unfortunate choice from a rigor standpoint, but this is common usage and will not change the usage in the utility industry. For our purposes, we must adopt somewhat greater rigor in terminology, as well as practice, since we wish to use such measures as a means to rigorously define both Properties and Qualities, but especially Qualities. This is because of the need to address the key questions listed earlier relating to analytical evaluation of architectures.

Some utility “metrics” actually measure the opposite of what they are supposed to measure. A good example is the set of reliability metrics commonly used in the electric power industry. Most of these reliability “metrics” actually measure unreliability.

2.6.9 Mathematical Rigor for Qualities and Properties

Properly speaking, what we want for our purposes are norms, in the terminology of abstract mathematical spaces.

- Norms measure the “size” of a thing
- Metrics measure the “distance” between two things
- Norms are said to induce metrics

We want the definitions of Qualities to be as nearly orthogonal as possible, so in practice we should define them in a Hilbert space. Underlying this space, we need a basis that lets us define norms in terms of two key parameters: time and geospatial extent. In practice, many norms can be defined in terms of delivery points, since known mappings relate such points to geospatial location.

Properties would benefit from the same rigor but due to the large number typically needed, this is not always entirely practical. The issue is to some degree is resolvable using the mapping to Qualities as long as the Qualities form an orthogonal basis set. Care must still be taken to keep Property definitions as clean and simple as possible. Considering them as a set is helpful in this regard.

2.6.10 Some Notes on Property and Quality Definitions

It is important to avoid relying upon common English definitions of property and quality names, even though the names may seem descriptive. Areas of particular ambiguity involve terms like flexibility and adaptability for example, and reliability and resilience. One of the methods for resolving ambiguity involves the application of temporal, geospatial, and intensity scale. Adaptability may be viewed as having two components, parametric and structural, which operate on very different time scales (fast for parametric, slow for structural) and may also differ in geospatial scale. Reliability and resilience may be viewed as essentially similar except that reliability operates on “routine” time and scale, whereas resilience applies on a special time scale and magnitude related to special events. Utilities essentially reflect this now in how they handle reliability metrics during events such as hurricanes.

The following is a set of grid system qualities developed using the principles described above. Note that none of the qualities is an “ility”. Each has a preliminary mathematical definition (not shown here) except for the last (which is to be developed in subsequent work). Definition of the last quality in the list and proof of mutual orthogonality of the entire set based on their mathematical definitions are tasks yet to be completed.

1. DELIVERS – the grid provides the amount of energy customers want, when they want it, and in the form they want
2. CONSERVES – uses all resources sparingly, especially those that are not replaceable
3. PRESERVES – minimizes wastes and emissions
4. PROTECTS – provides safety for itself, users, utility workers, and the public in general
5. ADAPTS – adjusts to changing conditions on both fast (parametric) and slow (structural) time scales
6. ENABLES – provides broad access and support for customer service, energy innovation, and value realization
7. MERITS – provides sufficient useful capability and public good to support continued public and private investment

Item 1 addresses basic functionality, and so encompasses many operational excellence issues that tend to get overlooked in grid “ility” discussions. Items 2 and 3 decouple input issues from output issues, something that is often overlooked when specifying qualities like “clean and sustainable.” Such decoupling leads to better definitions of unambiguous norms. Item 4 addresses the grid’s responses to failures and attacks. Items 5 and 6 both address aspects of how the grid changes. Item 7 addresses economic factors but in a broader manner than affordability alone.

It should be clear that multiple “ility” type properties may support any given quality, and any given property may support more than one quality

2.7 Markets and Controls

In electric power systems, both market mechanisms and control systems are used. In some cases, the markets and controls retain their separate identities and characteristics, even when they have some connection with each other. However, for organized central real-time markets, the market and control networks have converged, resulting in a platform upon which new value streams can and have been implemented, in accordance with the principles of network convergence. This platform includes the real time markets as optimizing elements within receding horizon control loops such that new value streams are easily implemented by defining new market products, as is happening in California with storage services for the grid.

To better understand electric system market-control relationships, consider the basic structures involving grid markets and control. This analysis presumes specific implementations for the relevant markets and control systems, meaning that data collection, control and market algorithms, and computational facilities are in place and operational. While it is obvious that control is pervasive throughout the grid, it is less obvious that that markets and controls can work together in certain combinations and for certain ranges of performance variables, and that there are regimes of these performance variables where market mechanisms are not applicable, so that only traditional control mechanisms can be applied. Two key variables that characterize how markets and controls for the grid can be integrated are the update rate of the market, control, or combination; and the number of endpoints (devices being controlled, market bidders, etc.) participating in the control or market processes. The regimes of applicability for markets and controls may be charted to illustrate the underlying relationships. It is possible and useful to relate system planning processes to the market-control regimes on this same chart.

The purpose of this representation is to answer two basic questions:

1. How do electric system markets and controls impact each other and where does each apply?
2. What happens to an existing market or control regime when the number of endpoints (or participants), or the required update rate, increases significantly?

Figure 2.22 below shows the regions of support chart for two classes of markets – real-time and forward- as well as control systems. In this paper, the dividing line is whether the market mechanism operates in a supervisory mode in relation to the control system or as parts of the control loop(s). The five minute, fifteen minute, and hourly markets are typically placed in the real time category, with the day-ahead and forward markets placed in the supervisory category. For completeness, the region of support for system planning is also included.

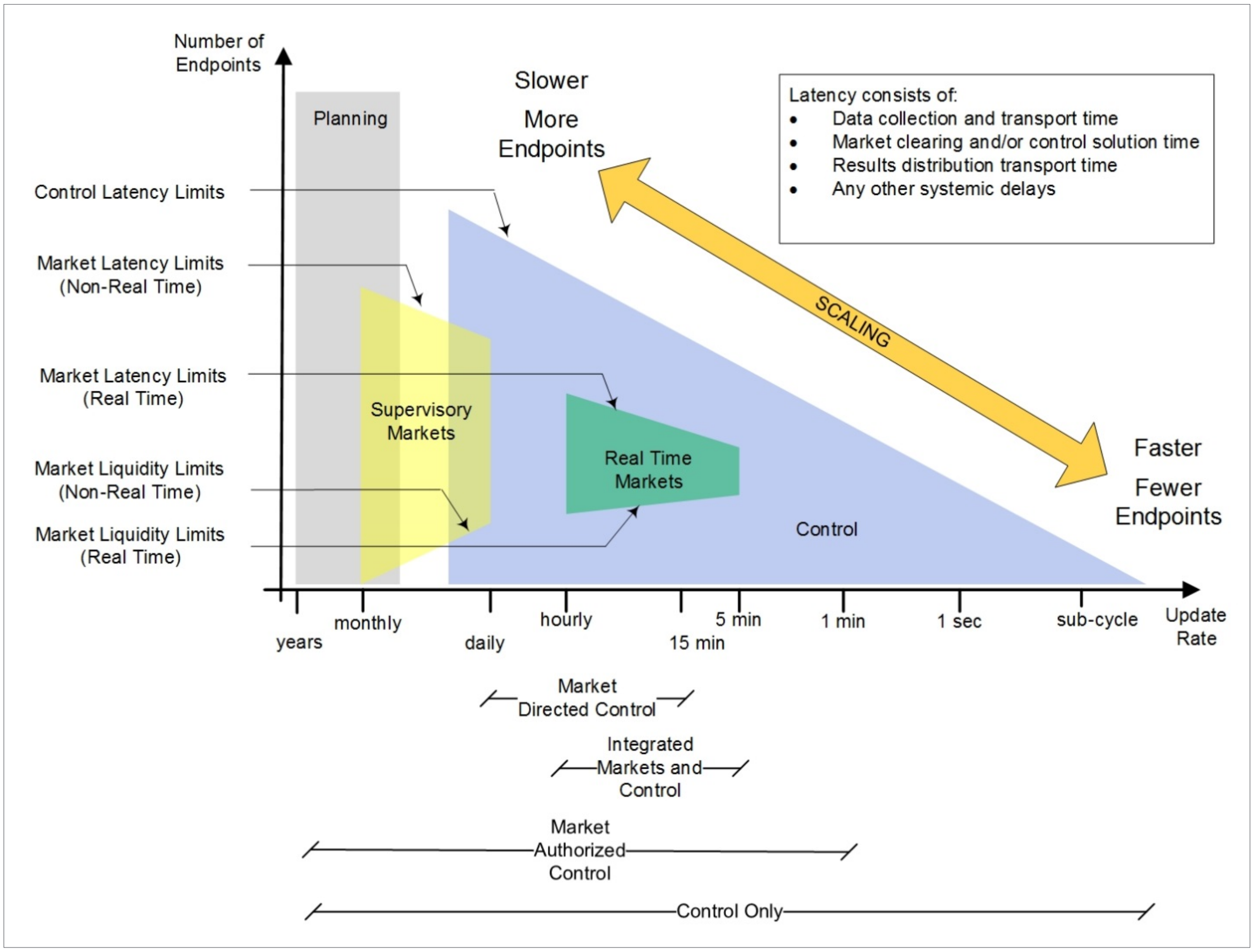

Figure 2.22. Regions of Support for Electric System Markets and Controls

Note that update rate is essentially a measure of temporal granularity, with faster updates corresponding to finer grain. The diagram allows us to identify three types of market-control combination, plus a fourth mode where only control is used, all of which are described below.

2.7.1 Principle of Market Participant Limits

In terms of participants, any given market implementation has both lower and upper bounds on the number of endpoints that can be involved. The lower bounds are not implementation dependent; rather they are market illiquidity limits. The upper bounds are due to algorithm complexity growth – as the number of participant increases, the market solution computation time increases until it finally reaches the update rate (cycle time) limit for the specified market. While this has not been an important issue for existing bulk system markets, the proposed vast number of the participating DER endpoints makes this a real consideration. At that point, either the market cycle will slow or a new market implementation will be required. A new implementation might involve additional computation assets, new market algorithms, or a change from centralized to distributed forms that support greater scalability than centralized ones may. In any event, a specific market implementation has an upper limit on participants that depends in part on the market update rate.

2.7.2 Principle of Control System Endpoint Limits

Similarly, control systems have upper limits on endpoints. The reason is essentially the same as for markets – with increasing numbers of endpoints, at some point any given control system cannot maintain its update rate, so either the update rate must decrease or some change in the control system must be made. Control systems do not have a lower endpoint limit of the type that markets have.

2.7.3 Principle of Market Update Rate Limits

The update rates shown for markets in Figure 2.22 are derived from present practice and so represent the bounds as they exist today. It is technically feasible to move some of these bounds, but for substantial reasons such as nonlinear growth of computational complexity and therefore computational time on a given hardware platform, there are still limits on, for example, update rates for real time markets. These granularity limits depend on a combination of technical and business value elements, but are nevertheless, very real.

2.7.4 Principle of Control System Update Rate Limits

Control systems used in utility grid applications have update rates that vary over a much larger range than markets do. Depending on the type of control, update rates can span from very slow (unit commitment) to very fast (sub-cycle down to even microsecond level for power electronics like electronic stabilizers, flow controllers, and solar inverters). A key aspect of the control system region of support is that, for any given control structure or mechanism, the maximum number of endpoints is a declining function of update rate, so that at very fast rates, a few or perhaps only one endpoint is involved (e.g. control of a DSTATCOM voltage compensation system that updates at a sub-cycle rate, say, four milliseconds), whereas, for slower rates (say, the typical four second SCADA cycle) the number of points may be large (numbered in the tens of thousands). Some functions, such as distribution capacitor control, generator unit commitment, and seasonal grid configuration are control system applications for which the update rates can be quite slow, measured in anywhere from minutes to months.

Architectural Insight 6

The architecture and design of combined market-control (Transactive Energy) grids must recognize the boundaries on each type of market-control interaction. In particular, there are certain classes of grid management problems that are not compatible with market mechanisms and therefore must be treated strictly as control problems whereas other problems can be treated as optimization problems which may best benefit from the use of market mechanisms as the optimizing principle

As shown elsewhere, there are multiple market-control structures. In some, the very fast control loops can be essentially supervised by slower market functions. The design of the nested and hierarchical structures involved should be informed by existing knowledge of such structures and their dynamics available from control theory.

3.0 Part 3: Selected New Architectural Views

In this section, certain new architectural views will be developed. Some are reference models and some are structure representations. All are aligned with the structural focus and network-of-structures concepts established previously for Grid Architecture. The specific topics in this section are:

- Control reference models for whole grids and for high-DER distribution
- Laminar Coordination structure
- Distributed Intelligence structure for whole grids
- Sensing and Measurement architecture
- Selected communication network architecture issues

Each view contains one or more Architectural Insights.

3.1 System Control Reference Model

This section provides reference control models for entire grids, including bulk energy systems, transmission, distribution, loads, and DER. It includes depictions for both non-DSO and DSO approaches to distribution management and grids with low DER penetration, behind the meter load reduction, and high DER penetration. These structural models reveal insights regarding hidden coupling in the grid and the full scope of Transactive Energy.

Appendix B contains two diagrams for full grid control. One presumes centralized ISO/RTO-level dispatch of DER and the second presumes distribution-level DER dispatch. On both cases, the full scope of control includes planning and so the set of time horizons for control span milliseconds to multiple years.

Architectural Insight 7

In a complete systems view of the grid, planning processes and associated capacity markets (where they exist) must be considered part of the overall grid management and control system. The functions of the planning processes and capacity markets reflect not just physical grids and assets, but also social, public policy, and regulatory dynamics.

3.1.1 Control Structure and Dependency

Controls systems are one of the classes of structures in the network of structures paradigm used in Grid Architecture. Consideration of control structure can reveal dependencies that impact control design. Figure 3.1 below illustrates control interdependence along with several forms of control dependency.

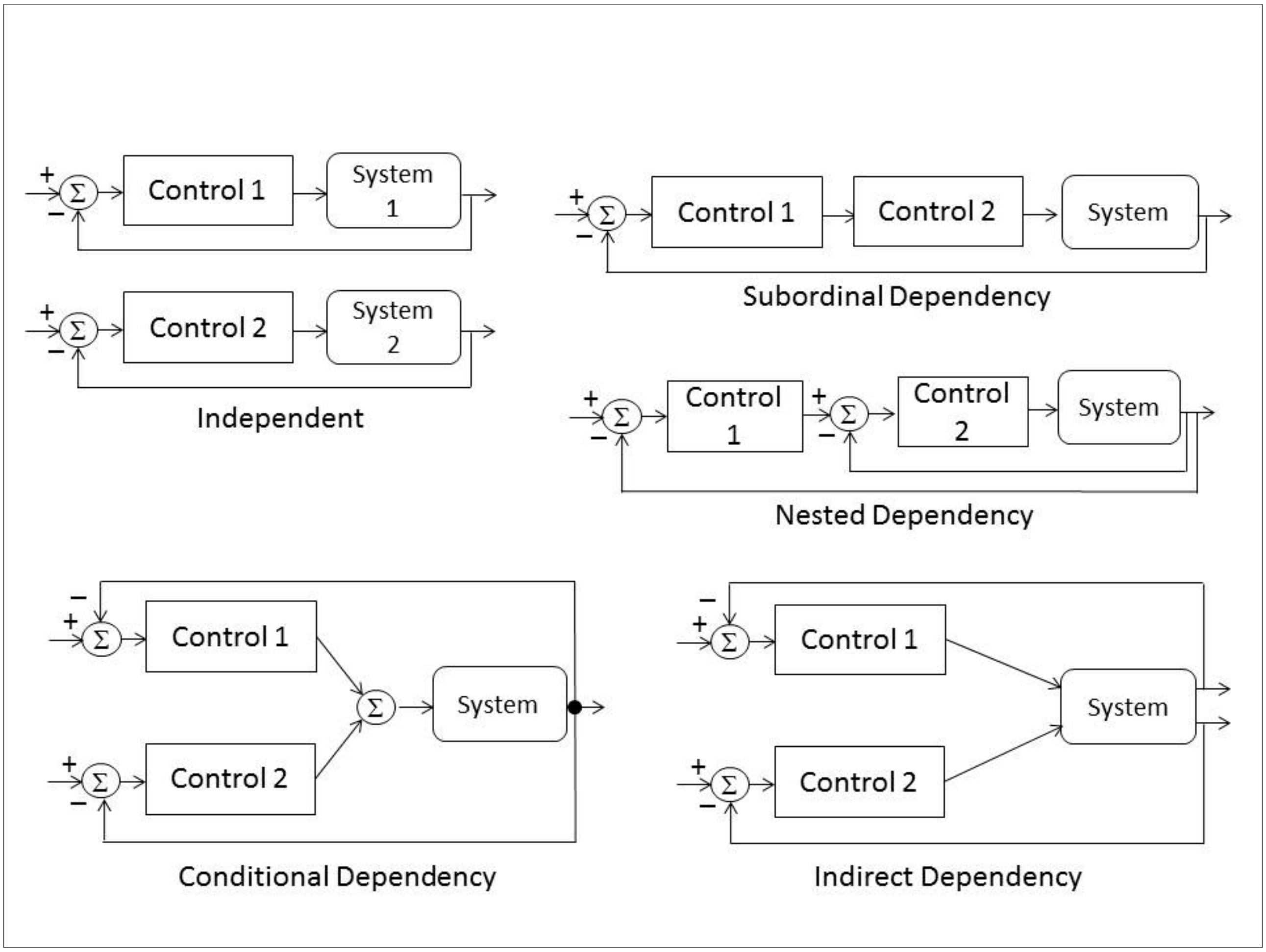

Figure 3.1. Control Dependency Structures

These structures may be designed but in systems with ultra-large scale complexity they may occur unintentionally. Consequently, is it necessary to analyze control structure as grid modernization solutions are designed but also as grids evolve, since such evolutions can create new dependencies.

3.1.2 Grid Control Model Construction

The grid control model will be built up in stages so that its complexity is comprehensible. Figure 3.2 shows the basic system to be controlled. The Bulk Energy System (BES) includes both conventional and variable energy resources, as well as utility scale storage and inter-Balancing Area interchanges. The distribution level includes both behind-the-meter DER (net load reduction) and distribution-connected DER. The fundamental control problem is to manage the BES resources and the dispatchable DER to match energy source flows to net load, while observing constraints on system frequency, voltages, and grid component load capacities. Note that from a control system standpoint, the transmission network and the distribution grids serve to provide summation of power flows from multiple sources, as well as connection of aggregated power flows to the loads. This simplified system model will be used in the subsequent control structures.

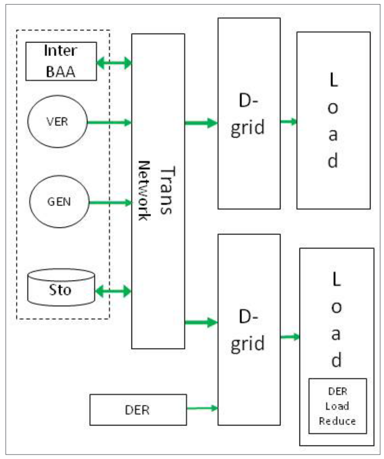

Figure 3.2. Basic System

Figure 3.3 illustrates basic bulk system control, including primary, secondary, and tertiary generator control, as well as supervisory control in the form of generator dispatch. This model depicts a grid prior to significant DER penetration except for behind the meter load reduction DER.

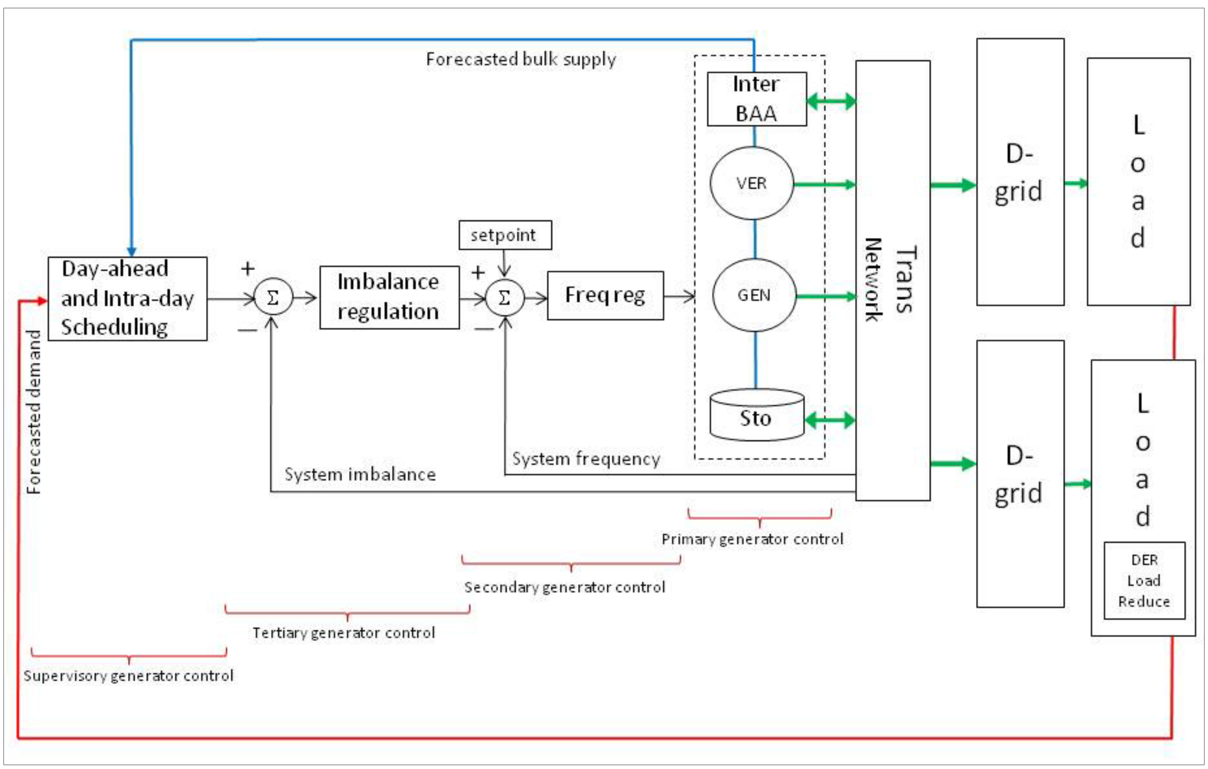

Figure 3.3. Basic Bulk System Control

For the purposes of this diagram, distribution level control is not shown. Neither is flow control, voltage regulation, synchronization, or stabilization. Note that the fundamental form of system control has three nested loops (primary, secondary, and tertiary generator control) and one supervisory level of control, which may be viewed as a trajectory planning control, where the trajectory is defined by forecasted load. Primary generator control typically consists of three cascaded local loops at each individual device (details not shown here). The system frequency control loop is closed around an entire Balancing

Authority Area, as is the imbalance loop (actually imbalance and interchange). The secondary control loop (load frequency control) operates on a four to six second update rate. In the case of an ISO or RTO with centralized markets, the imbalance and interchange functions are implemented via five and fifteen-minute update markets often referred to as the real time markets. The day-ahead and intra-day scheduling function provides hourly updates even though they may have been calculated up to a day in advance. In the ISO/RTO case, this function can also be implemented via a market mechanism. Considering the tertiary loop update rate to be five minutes, this structure provides for each loop to have an update rate about an order of magnitude slower than the one immediately inside it.

Figure 3.4 adds DER control to the mix with a proposed loop structure of its own. In this model, distribution level Volt/VAr regulation is explicitly shown, with DER able to participate in this regulation, in addition to standard grid Volt/VAr regulation devices for which the detail is not shown. The proposed loop structure for DER control that is shown here parallels the structure for bulk system control.

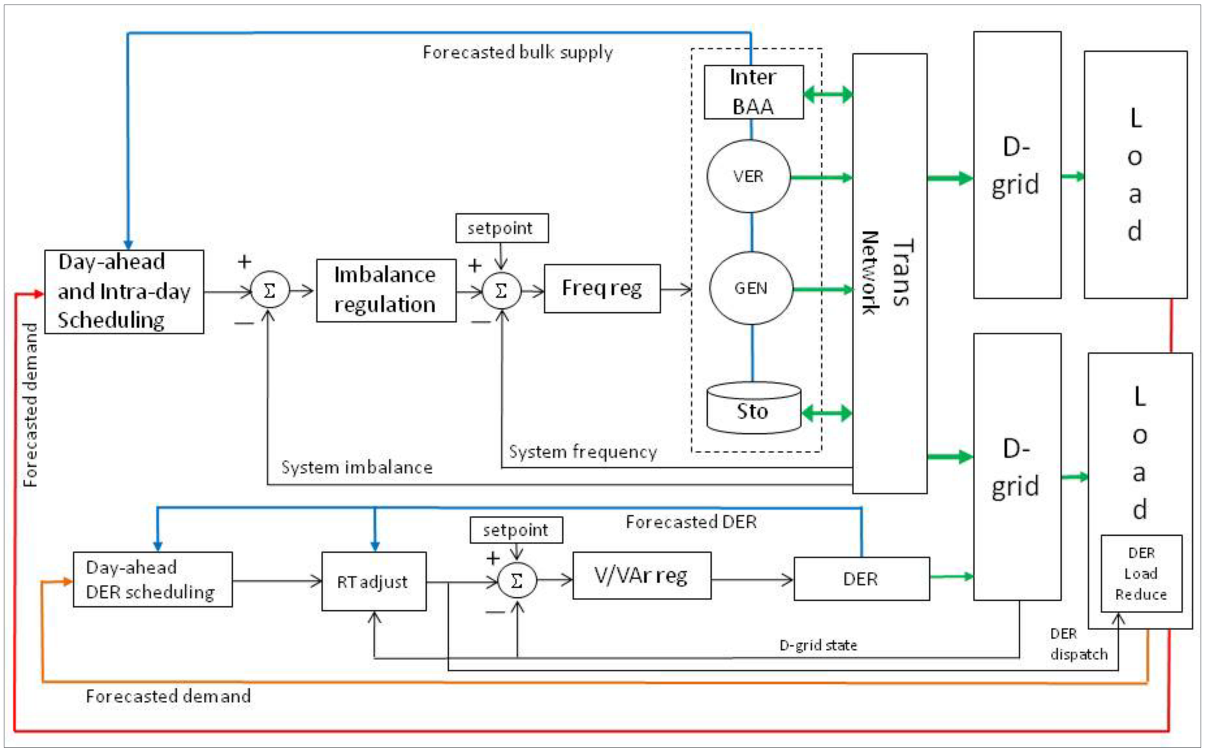

Figure 3.4. System Control with DER

Figure 3.5 includes the planning process and associated capacity auction markets into the model. These constitute an additional loop closed around the system, with very slow dynamics compared to what is usually considered to be grid operations. Given that the planning process can provide quasi-static locational values for distribution that can be used in place of actual dynamic values in the early stages of high-DER grid modernization, and given that planning drives changes in grid structure, it is not just reasonable but necessary to view planning and capacity auctions as elements of grid control.

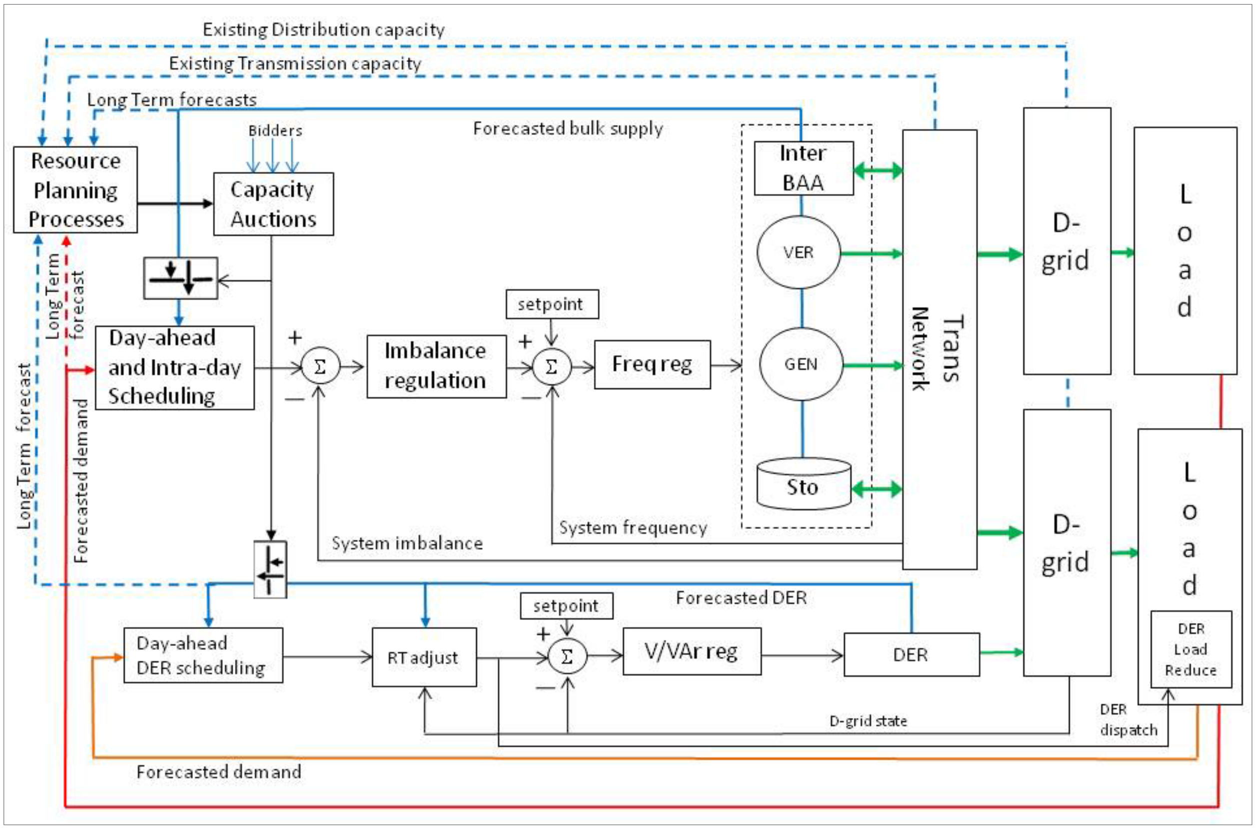

Figure 3.5. System Control with DER and Planning Processes

Architectural Insight 8

The recognition that planning has a significant impact on and relevance to not just deployment but actual operation of DERs is a significant reason why tools for planning should be integrated in some fashion with tools for control.

This whole system control model also makes it clear that in areas where organized central markets exist, the corresponding bulk systems already implement Transactive Energy. As DER penetration proceeds, if market mechanisms are combined with the necessary control mechanisms, then the Transactive Energy model will extend to the full grid. Transactive Energy therefore should be thought of as a global approach to grid planning and operation that combines control and market mechanisms into a converged platform and set of value streams.

3.1.3 Hidden Control Coupling in the Grid

In order to understand the hidden coupling issue, the diagram from Figure 3.4 will be simplified in stages. Figure 3.6 shows the first stage of simplification.

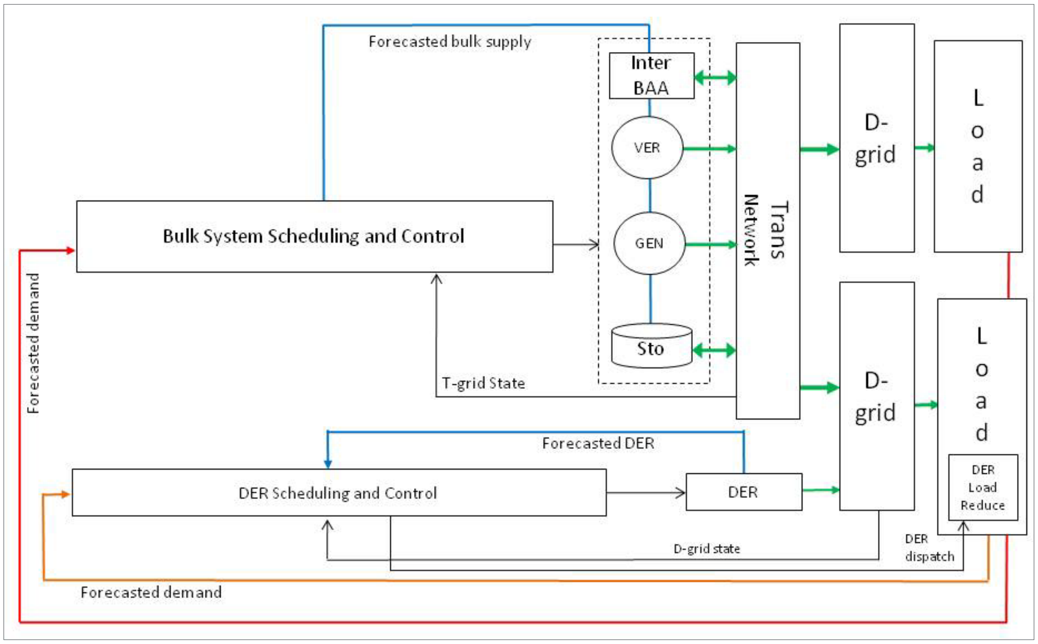

Figure 3.6. First Stage of Simplification for Coupling Analysis

In this simplified diagram, the bulk system controls have been condensed into a single box, as have the DER controls. Separate grid state feedback signals are provided to the two controls, and the forecasted demand (which is actually the reference trajectory for dispatch) could be common to both or not, depending on the implementation of the DER system. The issue of how these signals are handled will become significant shortly.

The second stage of simplification is shown in Figure 3.7. Here the basic feedback loop structures are evident.

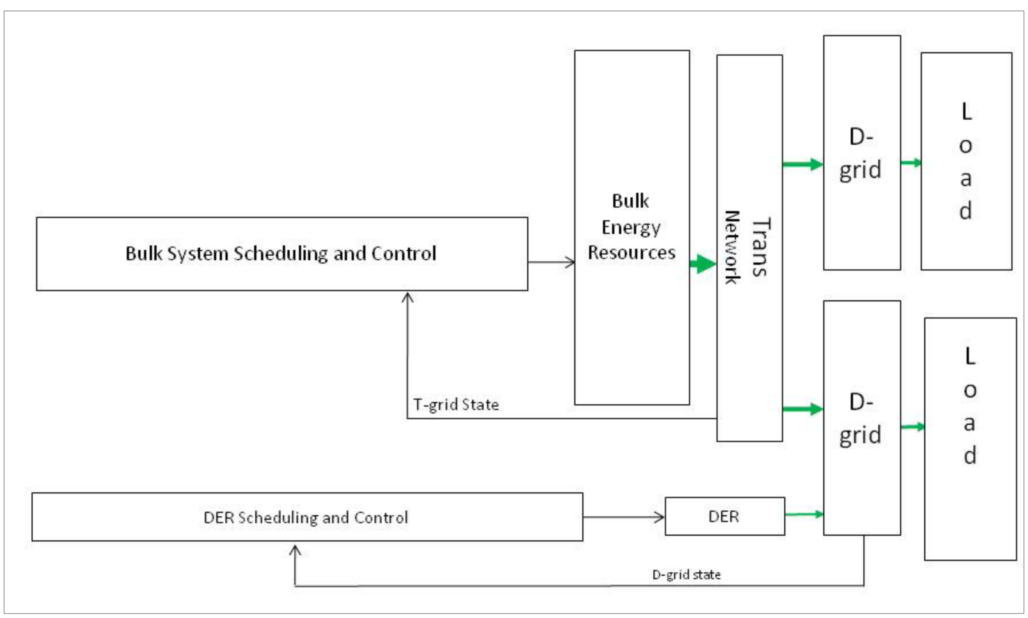

Figure 3.7. Second Stage of Simplification for Coupling Analysis

In this version, forecast information flow has been hidden to concentrate on real time operations and all of the bulk energy sources have been consolidated. Considering the lower D-grid and Load, it is now possible to clearly recognize coupling of bulk system and distribution level control. The coupling occurs at the distribution grid level and can be either conditional or indirect, depending on how feedback and control outputs are structured.

Architectural Insight 9

This form of coupling is present in all grids with bulk systems transmission connected to distribution grids that have distribution connected DER. At low DER penetration and with slow dynamics, the issue is inconsequential. But at high penetration and with fast dynamics, this coupling is an important issue with architectural and control design consequences. A crucial issue is whether or not both controls get the same feedback. In order for them to be the same, all of the distribution state information must be available at the bulk system control in real time (for all of the connected distribution systems). Such a requirement presents scaling issues that impact data architecture, communication structure, and control design.

Control design must take the form of dependency into account. With large penetration of DER, improper control design can lead not only to distribution reliability issues but also bulk system instability. From an architectural point of view, a choice must be made on the form of coupling to be admitted and this must align with other structures. Ultimately, the question of central grand optimization vs. distributed implementation for DER control is strongly connected to the hidden coupling problem.

3.2 Distribution Control/Communication Reference Model[25]

This section describes a reference model that illustrates key aspects of the new distribution problem domain from a control point of view. It presumes high penetration of DER, and a DSO model[26] for managing distribution operations.

Figure 3.8 below depicts a portion of a distribution system in which DER's of various kinds play significant roles. In addition to wind and solar generation sources, the model incorporates responsive loads, transactive buildings and a microgrid. It also contains three levels of storage: substation, neighborhood, and behind the meter. Power electronic flow control is depicted via inline flow controllers and solid state transformers but sectionalizing is via standard reclosers. Partial meshing of feeder primaries is depicted, with the inter-tie being a power flow controller instead of a switch. The feeder primaries are instrumented with line sensing and Volt/VAr regulation is done at various feeder locations. Fast voltage stabilization is provided via power electronics at the feeder level.

[25] This section is abstracted from a paper by J. Taft, L. Kristov, and P. De Martini, A Reference Model or Distribution Grids in the 21st Century, PNNL-24463, available from Pacific Northwest National Laboratory.
[2] P. De Martini and L. Kristov, Distribution Systems in a High Distributed Energy Resources Future: Planning, Market Design, Operation and Oversight, October 2015, available online at: https://emp.lbl.gov/sites/all/files/FEUR_2%20distribution%20systems%2020151023.pdf

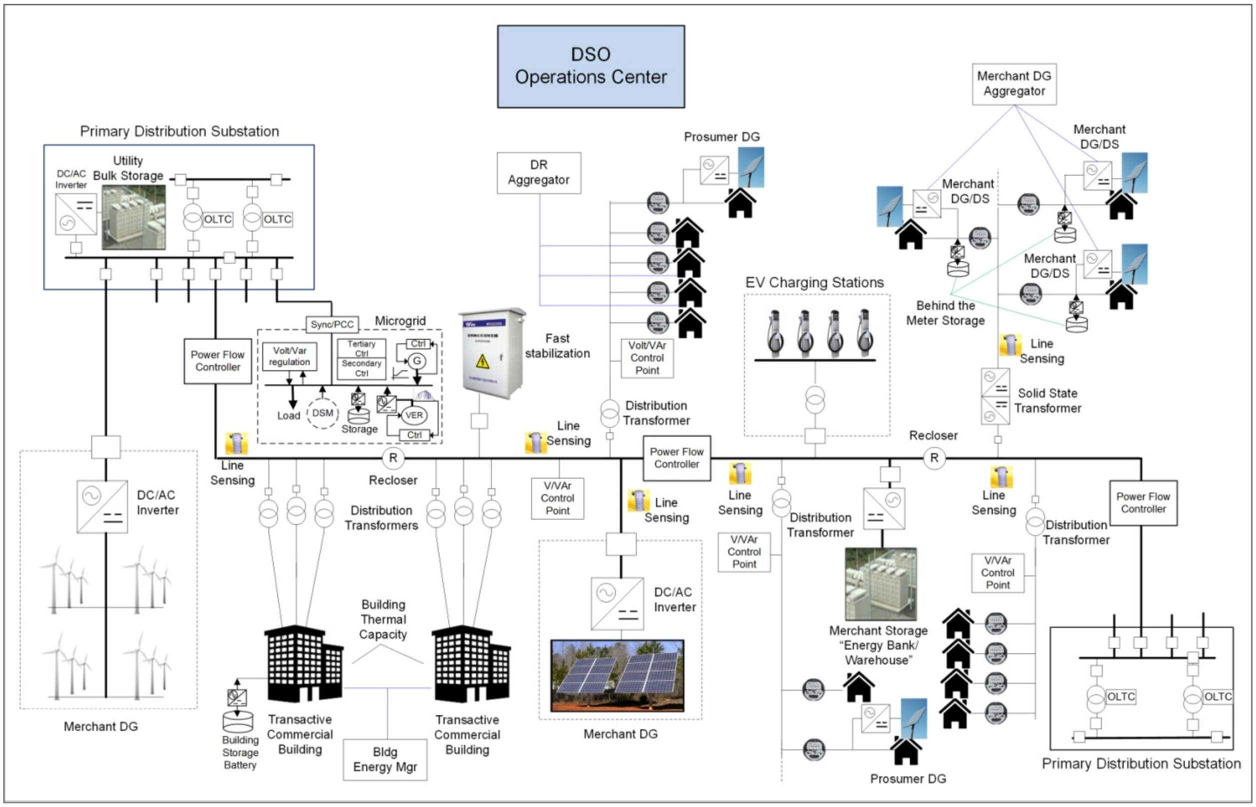

Figure 3.8. Advanced Distribution Reference Model Physical Environment

In this model, the distribution system is managed by a Distribution System Operator (DSO). While there are a range of DSO models under consideration in the industry, this reference document presumes that the DSO has substantial responsibility for coordinating DER operation in its service territory and handles the interface to the bulk system Transmission System Operator at an LMP node or transmission/distribution substation.[27] Figure 3.9 below illustrates a general control environment for distribution under the scenario of large penetration of DER and consequent reorganization of the distribution service provider to incorporate the necessary DSO functional capabilities. Distribution service is provided by a combination of DSO and Distribution Owner (the entity that owns the distribution system assets and is typically responsible under state or federal law for their safe and reliable physical operation and maintenance). Note that in the short run, DER resources will continue to bid directly into ISO markets (dashed green line). Eventually, the scalability issues and reliability compromises inherent in this approach will result in all DER being bid through the DSO, even if some is intended for system support via the ISO markets. In that case, the dashed green line would not exist.

In this environment, the DSO structure and the penetration of DER impact markets, control, measurement and verification, and communications profoundly. Key aspects of this model result in an increase in the number of channels through which the utility interacts with its consumers, prosumers, and merchant suppliers, which introduces new requirements for distribution control systems and communications networks.

[27] P. De Martini and L. Kristov, Distribution Systems in a High Distributed Energy Resources Future, Future Electric Utility Regulation Series, Lawrence Berkeley National Laboratory, available online at: https://emp.lbl.gov/sites/all/files/FEUR_2%20distribution%20systems%2020151023.pdf

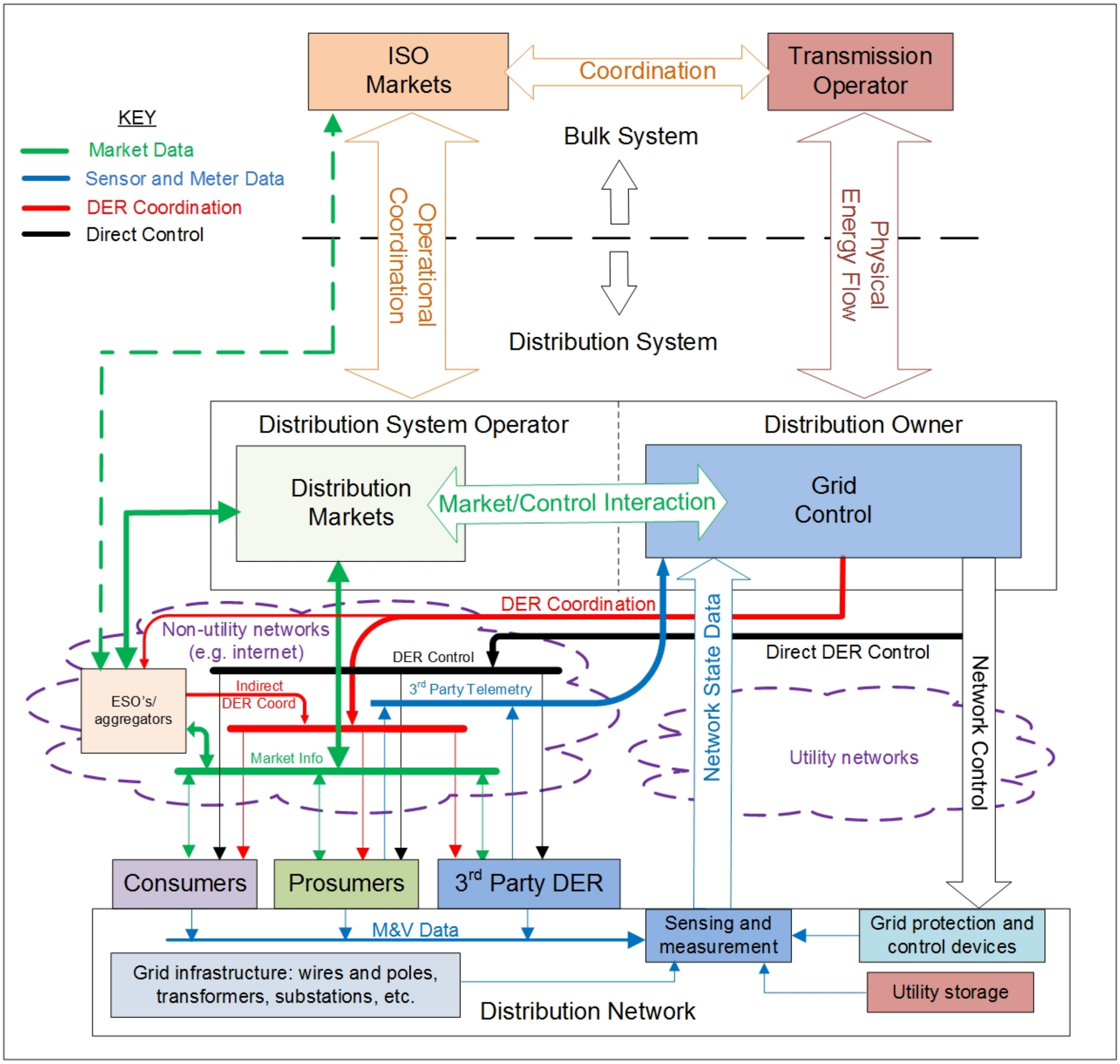

Figure 3.9. Advanced Distribution Reference Model Control Environment

3.2.1 Ownership of DERs

Four types of DER ownership are depicted in the model. Consumers may participate in Demand Response programs – these may comprise residential, commercial, and industrial facilities as well as microgrids (including transactive buildings). Prosumers may also provide Demand Response (or more generally Net Load Reduction via DR, DG and/or DS), as well as other power and energy services. Merchant and non-profit third party organizations (such as municipal utilities and Community Choice Aggregators[28]) will own DER (which may be installed at residential, commercial, or even industrial premises not owned by the third party) specifically intended for both customer load management as well

[28] CCAs are direct access providers created by city or county governments for their areas that utilize an Investor Owned Utility distribution system.

as grid services or other energy or capacity value propositions. Finally, the Distribution Owner may own DG and/or DS components for use on their grids.

3.2.2 Communications Network Channels (purple clouds)

The future distribution model has two types of communication channels: the familiar utility network(s) that connect to grid devices, and non-utility networks such as the internet and other third party-owned networks (e.g., the Harris national fiber network). It will be necessary to connect via the internet because most DER assets will not connect through utility networks but will be routinely equipped with internet connectivity. These devices will in general have "Cloud" connectivity and in fact some useful services, such as aggregator services and analytics, will be provided by Energy Services Organizations (ESOs) via the Cloud in such a way as to appear seamless. Consequently, such services are depicted as part of the Cloud in Figure 3.9.

3.2.3 Market Access Paths (green lines)

DER assets can be bid into DSO markets either directly or via aggregators. In either case, the communication path is via the internet and Cloud. In one variant of the DSO model, DER may bid directly into the ISO market, individually or as elements of aggregated virtual resources, as shown by the dashed green line in the diagram. In another variant of the DSO model, that dashed green line does not exist and DER access to the ISO bulk markets is only through the DSO. In both cases the ISO's grid visibility extends only to the T-D interface. Therefore, although market bids, settlement-quality meter data and other financial information flow along the green lines, DER dispatch coordination does not (see Control and Coordination Paths below). Due to the need for dispatch coordination by the DSO/DO, a question for further consideration is whether the added coordination challenges of allowing direct DER participation in the wholesale market (dashed green line) is outweighed by the benefits.

3.2.4 Control and Coordination Paths (red and black lines)

In the model, there are two different paths for DER coordination (in red), one path for direct DER control (in black), and another path for standard grid control. The three DER paths make use of the internet for communications because that is how the non-utility DER assets are connected. Two are coordination paths: one for direct coordination of DER by the DSO, and one for indirect coordination via an aggregator. The third path is for direct control of DER by the DO portion of the utility. An example would be command of DG or DS inverters for reactive power control. This form of control resembles traditional grid control but the assets being controlled do not belong to the utility and do not have utility network connectivity.

The fourth path for traditional grid control makes use of standard utility networks. It is possible that some DOs will employ the internet or other public shared networks (such as municipal Wi-Fi), but even so, all four paths will still act as independent virtual private networks for security purposes regardless of how the physical networks are arranged.

3.2.5 Sensing and Measurement Paths (blue lines)

Sensing and measurement data will arise for three distinct classes of sources: grid sensors and devices, meters, and DER devices and systems. Grid power state and energy state data will be collected in the usual manner, via SCADA and utility network(s). This includes meter data for both billing and DER measurement and verification. Given the complications that DER may cause on a distribution grid, distribution sensing will require somewhat sophisticated observability strategies, may include new kinds of sensors, and will certainly involve much greater data volumes and rates.

In addition to utility-owned sensors, DOs will use data from the instrumentation incorporated in DER devices. Such telemetry will travel via the internet and Cloud, so that network state data will arrive at the DO through two possibly distinct channels (internet/Cloud and utility networks).

> **Architectural Insight 10**
>
> The distribution grid control and coordination problem itself is changing rapidly and the gap between traditional distribution grid control and the requirements of the newly evolving environment is widening rapidly. The potential presence of a mix of DER elements poses a new kind of control/coordination opportunity with as-yet unresolved complications. In addition, if some form of distribution level market mechanism is employed, the interactions between the market and the control/coordination mechanisms must also be considered, which adds another new dimension to Distribution Management System design. Locational value and locational density create considerations for the DER dispatch problem that do not have simple counterparts at the bulk system level, and the presence of aggregators can mask some of the locational characteristics of DERs, further complicating the problem of realizing best value from DER investments.

3.3 Laminar Coordination Architecture

3.3.1 Background

Modern electric power grids are an interacting set of networks, one of which, the coordination framework is partially hidden and partially missing. Such a framework can be established rigorously, but if not properly understood could result in unnecessary proliferation of new interface standards. By using proper architecture methods, a very small set of interface classes can be defined, such that the effort to define and implement interoperability standards is greatly simplified, along with attendant costs of both interfaces and system integration work.

3.3.2 Laminar Coordination as a Grid Structure

In the Ultra-Large Scale grid architecture view, a power grid is a network of interacting structures. Five of these structures are readily apparent: electrical infrastructure, industry structure (including markets where they exist), control structure, digital infrastructure, and regulatory structure. The sixth is the set of presently converging structures: transportation, fuel networks, and social networks. But one of the structures, the coordination framework, has traditionally been partially missing and partially hidden in existing power grids. Using the coordination framework as the seventh grid structure makes coordination explicit, and allows for its use in flexible configurations as needed for any specific grid. Recent work on the theory of network architectures[29] can make the grid coordination framework explicit, accessible, and complete. The application of layered decomposition and network utility maximization provide the rigorous formal basis for such a coordination structure, called the Laminar Coordination framework. This

[29] Mung Chiang, et. al., "Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures," Proceedings of the IEEE, Vol. 95, No.1, January 2007.

resultant framework is an idealization, chosen to have a regular structure and certain predictable properties[30] but which easily supports practical implementations.

Using layered decomposition this way requires translating the framework mathematical basis into something more tangible, but still in a rigorous manner. The sections below briefly describe the basis for Laminar Coordination, and derive its basic component and structure descriptions. Finally, the last section shows how to define the necessary interface classes, so that interface standards may be properly developed.

3.3.3 Mathematical Basis

In the field of distributed and hierarchical control, coordination is the means by which disparate control elements are kept focused on the common problem to be solved jointly. There are two primary classes of methods to accomplish this: goal decomposition and structure decomposition. Goal decomposition is further divided into state adjustment and incentive adjustment methods. Goal decomposition does not yield a basis for defining distributed structure as it is done in a completely centralized manner. As the name suggests, structure decomposition does yield a structural framework. Figure 3.10 illustrates the recursive decomposition process. The reference cited in footnote 29 provides the mathematical basis for this decomposition.

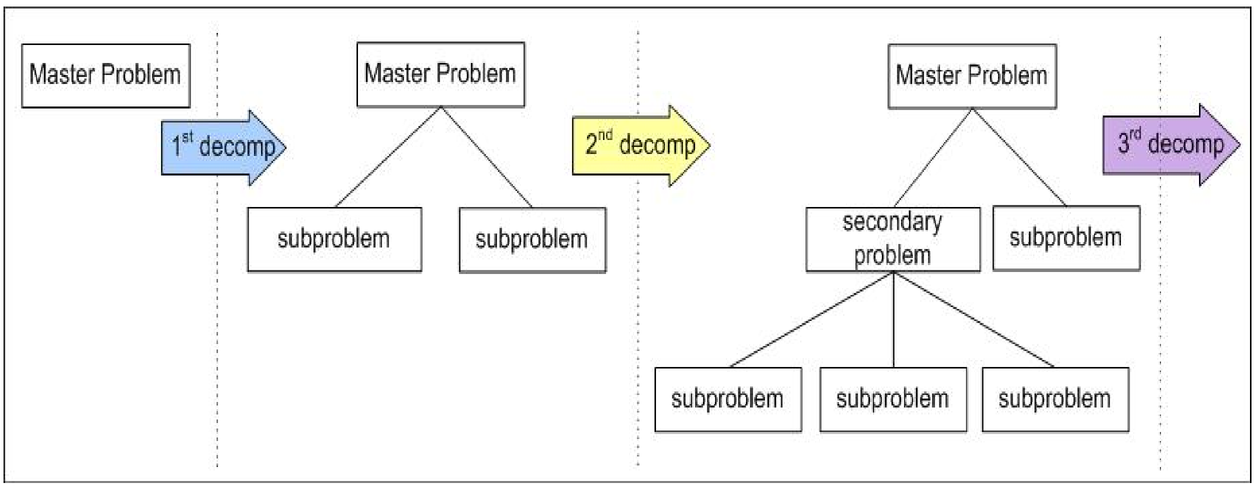

Figure 3.10. Layered Decomposition of Optimization Problems

The layered decomposition approach provides a basis that aligns well with time scaling and geographic encapsulation, which are key characteristics of electric power grids in the US. However, using a standard primal of dual decomposition one time yields a solution form that can be implemented in distributed form but this solution has a severe scaling problem. As Figure 3.11 shows, the iteration step size necessary to assure convergence becomes small with a rising number of endpoints and clearly cannot scale to the numbers of DERs that are anticipated in advanced grids. Using two decomposition layers with primal-dual decomposition does not actually resolve this issue, as the step size-endpoint relationship does not change for a wide class of practical problem formulations.

[30] Jeffrey Taft and Paul De Martini, "Scalability, Resilience and Complexity Management in Laminar Control of Ultra-Large Scale Systems," available online: http://www.cisco.com/c/dam/en/us/products/collateral/cloud-systems-management/connected-grid-network-management-system/scalability_and_resilience_in_laminar_control_networks.pdf

In practical situations, it is necessary to deal with existing system and organizational boundaries. The framework can accomplish this by creating a new coordination node for any specific system or organization. In the same way, southbound fan-out can be managed for scalability purposes. Coordination nodes may be physical or virtual, and the framework may be pruned in locations where no actual grid device or system exists.

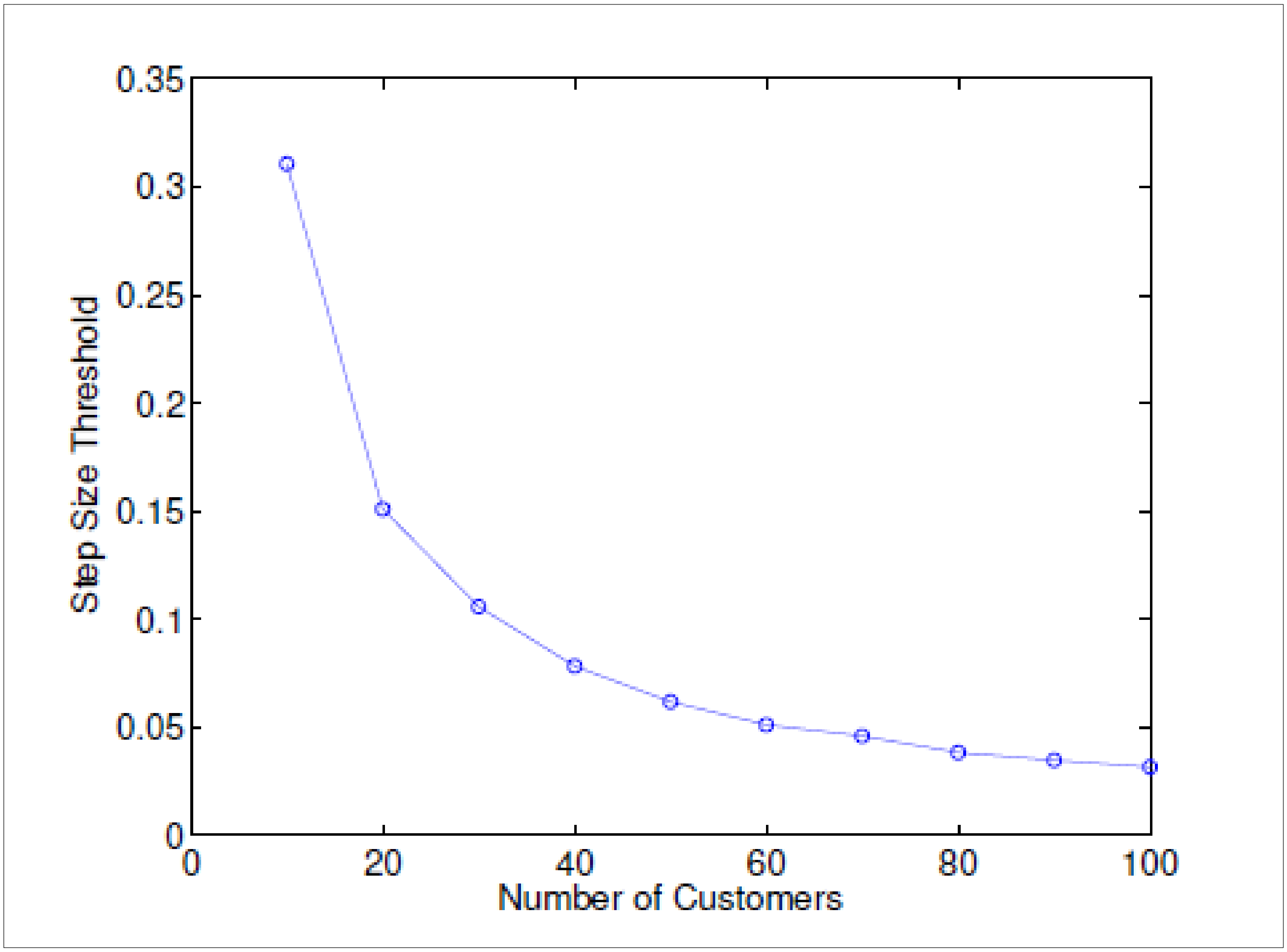

Figure 3.11. Layered Decomposition Step Size Convergence Effect

3.3.4 Normalized Structure

In the idealized form, the structure induced by the mathematical basis has a layered form, as shown in Figure 3.12. Each coordination node has an associated domain. This structure does not imply that the underlying grid or even its control must necessarily be hierarchical in nature. Instead this is reflective of the ability and necessity to represent spatio-temporal scaling in coordination. The induced coordination node structure is a recursive tree, where each tier or layer corresponds to a particular spatio-temporal scale. The model includes both inter-layer information flow and intra-layer peer-to-peer flows.

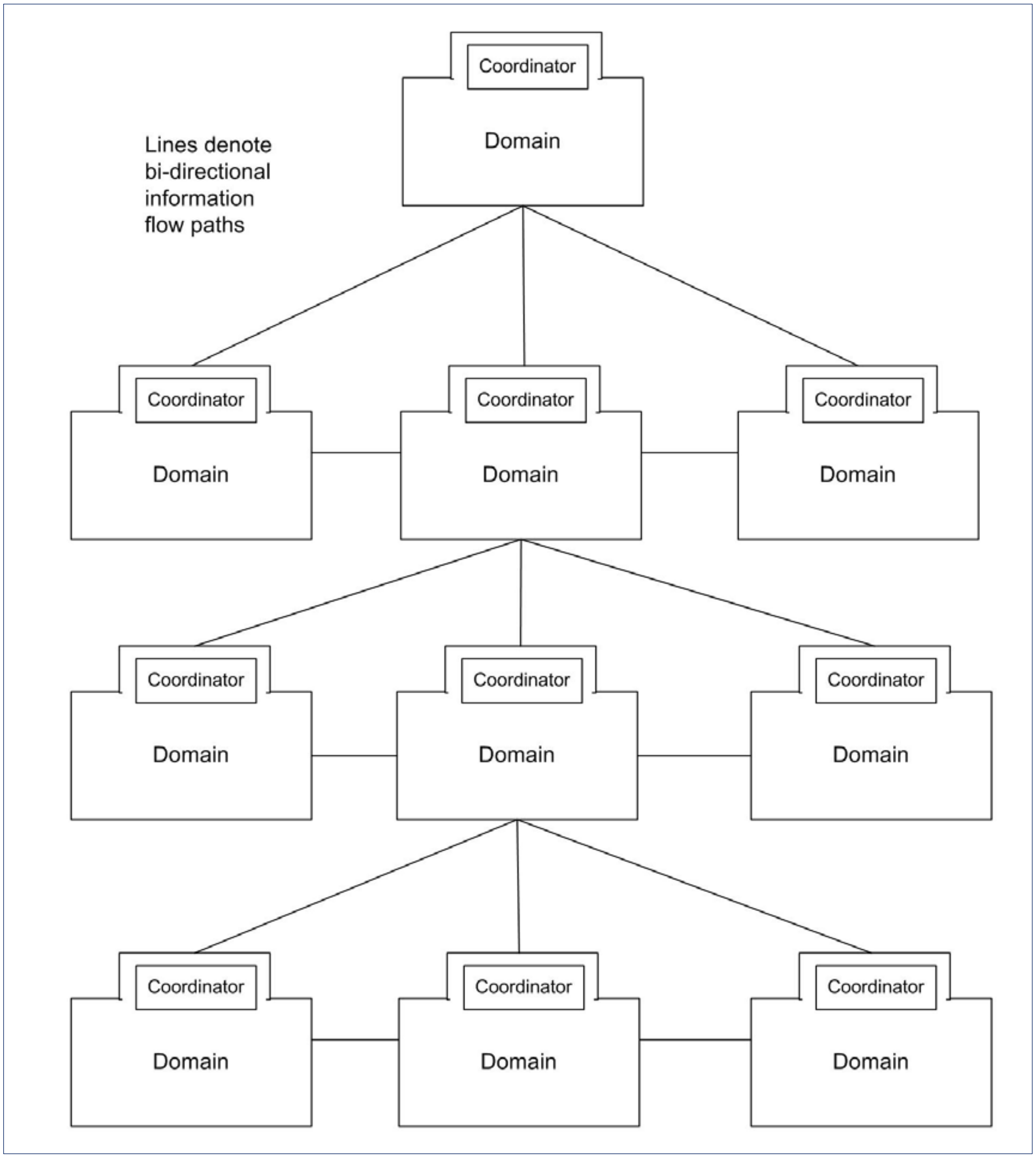

Figure 3.12. Idealized Coordination Domain Structure

The layered structure of the coordination framework derives from the mathematical basis and corresponds to spatio-temporal scaling; however, it maps well to existing grid control structure as shown in Figure 3.13. This is because existing grid control is largely based on geographic encapsulation, which leads to a structure similar to that of the Laminar Coordination framework.

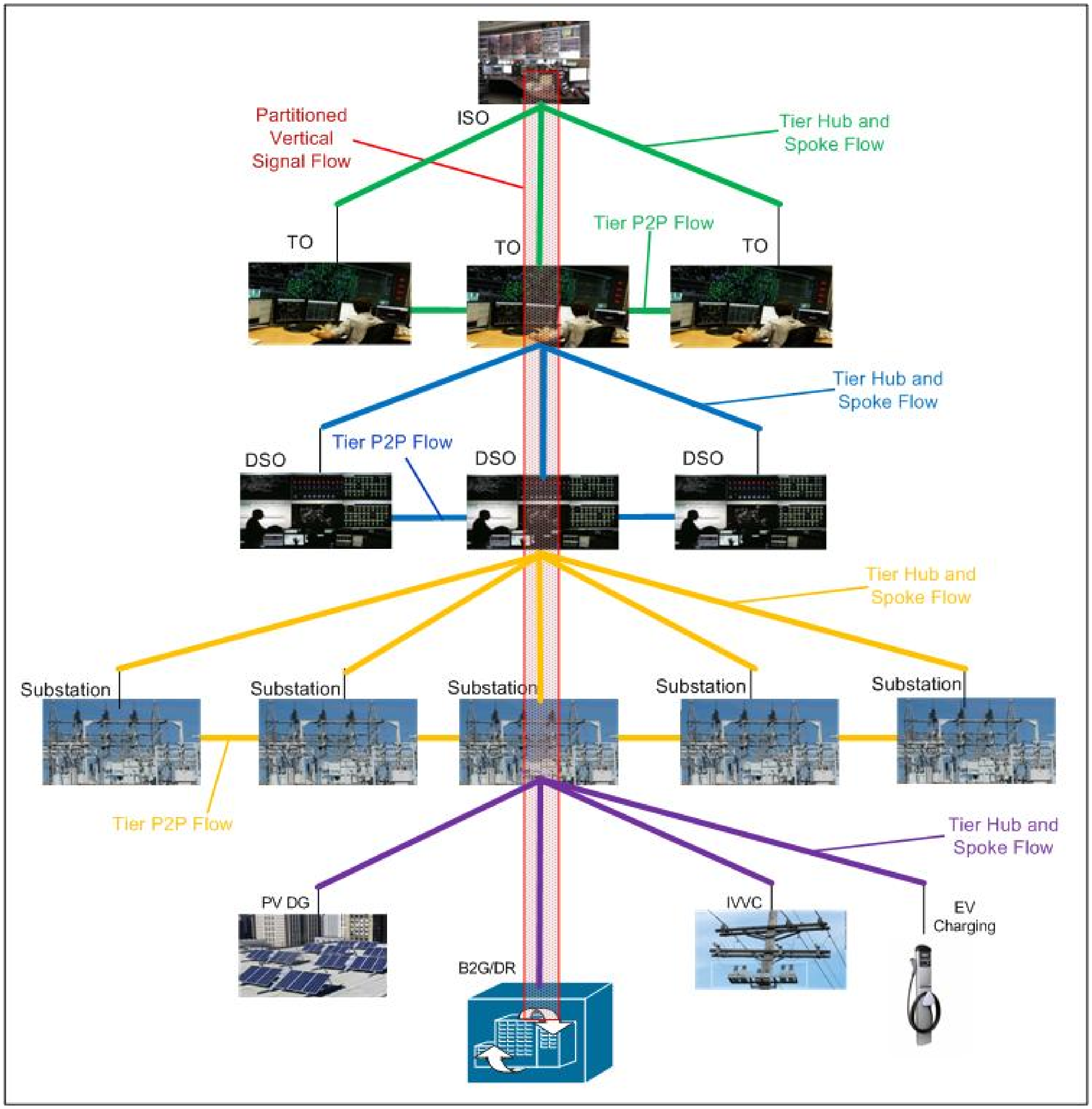

Figure 3.13. A Mapping of Laminar Coordination Framework to Existing Grid

3.3.5 Coordination Nodes

The layered decomposition breaks a large problem down into smaller connected optimization problems, arranged in a hierarchical manner. This implies that at each decomposition layer, a new set of nodes is defined, each of which must also solve its portion of the problem by solving a smaller problem in cooperation with the node above it in the hierarchy, as well as with its peers. Since any node may be a candidate for further decomposition, each node must not only be able to act as a bottom node for the master problem at the layer above, it must also be able to act as a master for a further decomposition node layer below. Thus the mathematics of layered decomposition implies a component with structure as shown in Figure 3.14.

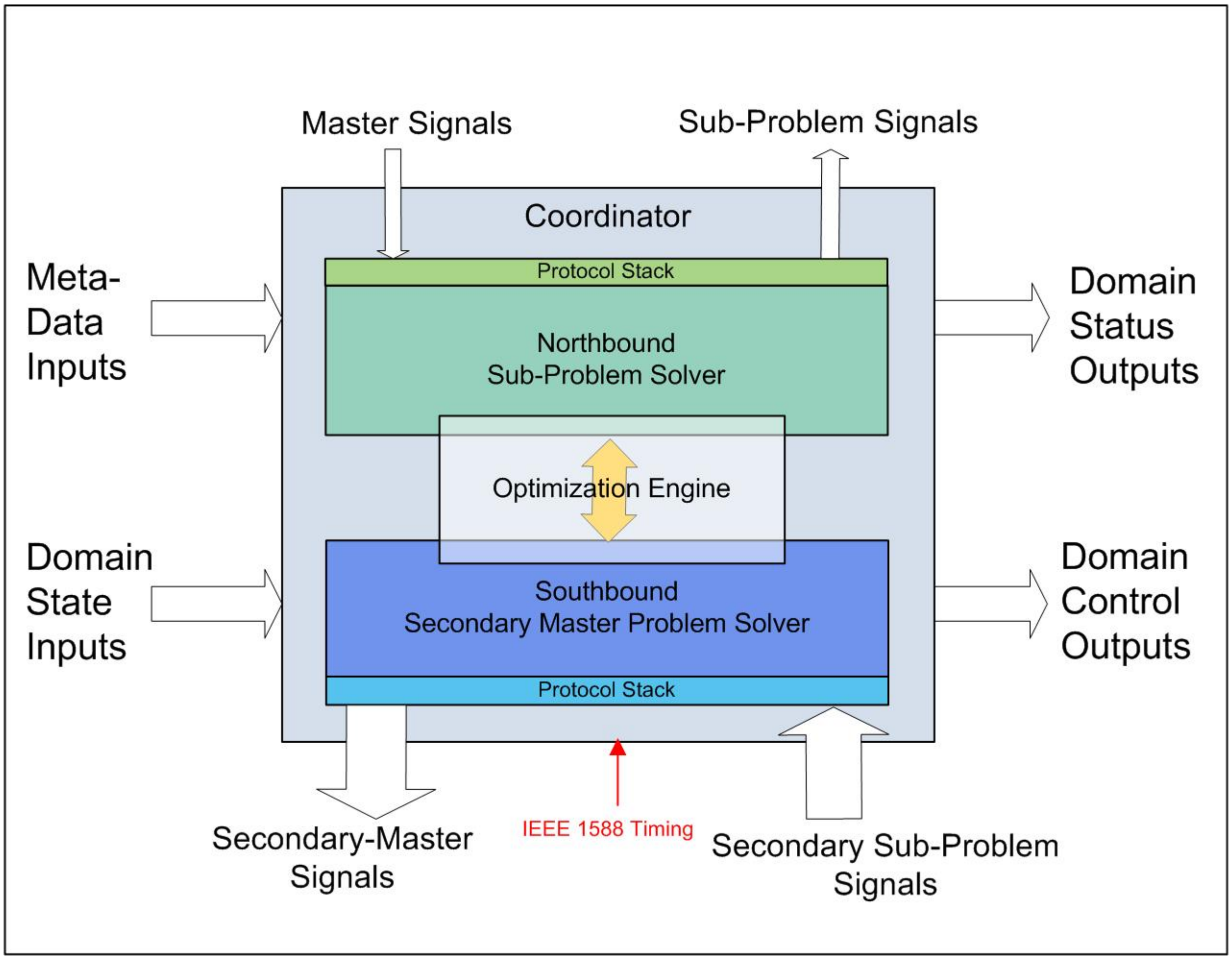

Figure 3.14. Basic Coordination Node

The coordination node has a northbound portion that participates in the upper tier optimization decomposition, as well as a southbound portion that acts as a secondary master for a secondary decomposition, if needed. The node must have an optimization engine, but its nature is not specified and may be different in different parts of the system. At the lowest layers it may be a simple equation computation embedded in a device, whereas at higher levels it may be a transactive node, a mixed integer linear programming application, a Newton-Raphson engine, etc.

3.3.6 Coordination Domains

The Laminar Coordination framework implies a set of coordination domains, each one corresponding to a single coordination node, as shown in Figure 3.15.

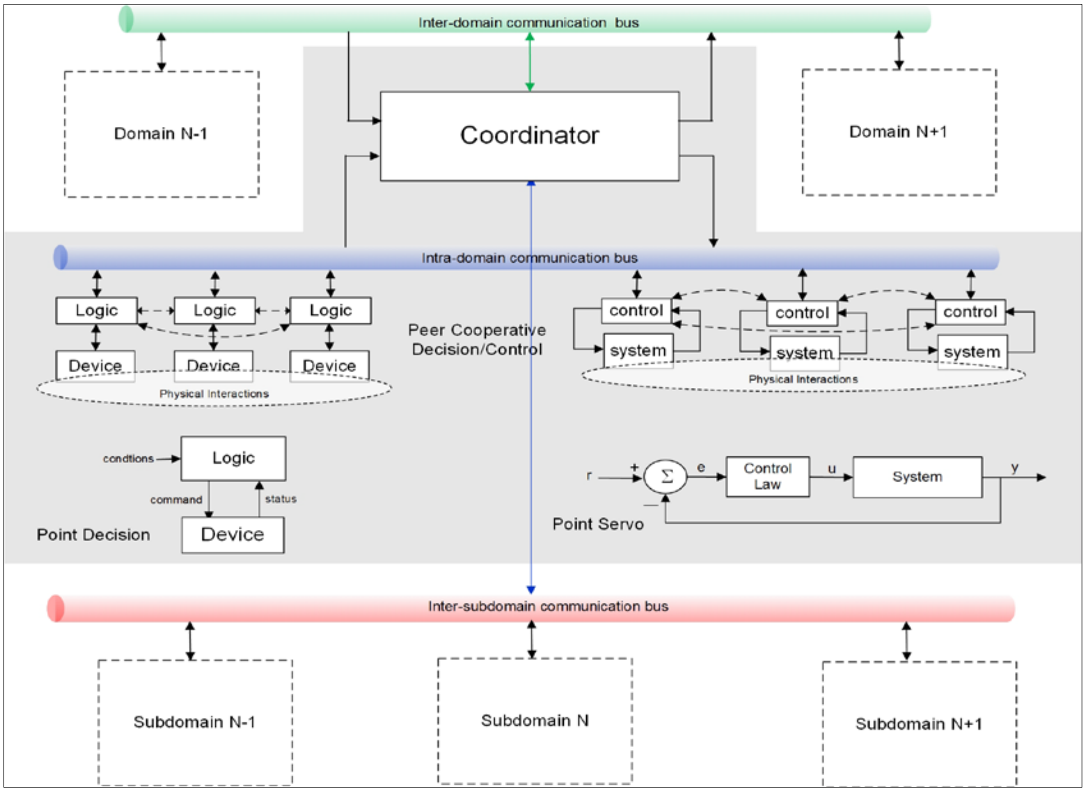

Figure 3.15. Typical Feeder Level Coordination Domain

The definition and scope of a coordination domain is level and scale dependent, meaning that a domain may be a small as a single device, or as large as a balancing area. In between, domains can include entire distribution service areas, or a signal substation service area, a single feeder, a feeder section, etc. The definition of a domain is a degree of freedom for the system designer. Note that a coordination domain may have a variety of devices and subsystems in it, some of which may be supervised by the coordination node, and some of which may even be directly controlled by the coordination node. A coordination domain may have an internal control communication bus (not necessary a distinct physical network) as well as northbound and southbound communications for the optimization nodes.

Domain coordination nodes interact with elements in the coordination domain as well as with higher level coordination masters and lower level coordination nodes. Since the elements are distributed and may require synchronization for control purposes, timing is distributed via the network.

3.3.7 Decomposition Formulation, Convergence, and Scaling

The underlying optimization problem can take many forms. Its use in Laminar Coordination was initially motivated by the need to extract a structure from a rigorous starting point, it can however, be used to formulate and solve actual grid control problems. Doing so provides further insight into the laminar structure and a significant class of control problems. Recent work[31] has shown that for a fairly general class of such problems, iterative optimization approaches work but do not scale to large numbers of endpoints because the iteration step size that guarantees convergence shrinks as the number of endpoint increases in such a way that the average number of iterations goes to infinity as the number of endpoints becomes large. However, in the distributed formulation that arises from layered decomposition, adjusting

[31] Work in progress at PNNL on structural properties of layered decomposition.

the form of decomposition can modify this issue to yield useful solutions than can scale reasonably with the number of endpoints. In addition, the concept of virtual batteries can be applied to assist in the decomposition by providing virtual decomposition nodes as needed.[32]

3.3.8 Interface Cut Sets

Once the structure has been determined, we may identify the interface groups by using the method of cut sets.[33] In this approach, cut sets define information flow boundaries and therefore interfaces (at the respective ends of the cut links). Figure 3.16 illustrates the relevant cuts. In a regular structure such as the one under consideration here, the cuts sets are quite simple and so will seem obvious. In more complex (less regular) structures, the cut sets can be torturous. An advantage of the structure under consideration is that the very same regularity that leads to an understanding of structural properties also provides simple interface cut sets.

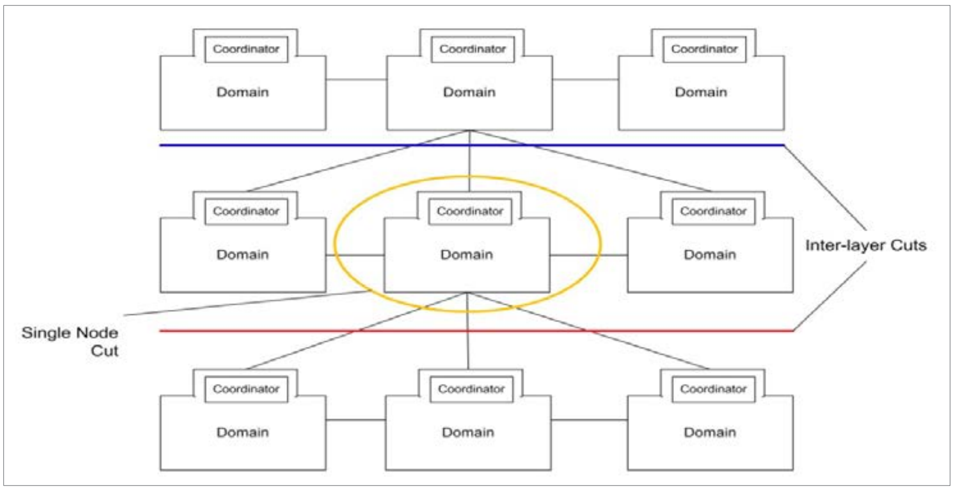

Figure 3.16. Coordinator Cut Sets and Interface Definition

3.3.9 Inter-tier Interfaces

The red and blue cut lines shown in Figure 3.16 serve to separate coordination layers. The set of links that intersect each cut line form the relevant cut sets, and identify the necessary interfaces between two specific tiers. Each interface is common to all the lines in a given cut set. Between tiers, the nature of the interface may be different as needed, but practically speaking the decomposition formulation ensures that a limited set of variations is sufficient.

3.3.10 Intra-tier Interfaces

After removal of the lines intersected by the inter-tier cuts, the remaining lines intersected by the orange oval identify the intra-tier interfaces. These are common across a given tier and likely are the same from tier to tier, but that is a degree of freedom for the system designer.

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[32] He Hao, et.al., Aggregate Flexibility of Thermostatically Controlled Loads, IEEE Transactions on Power Systems, Vol. 30, No. 1, January 2015.
[33] A cut set is a set of edges (links) in a graph which when cut, partitions the graph into two or more parts.

3.3.11 Nodal Cut Sets

Using the yellow oval as the cut line identifies all of the interfaces associated with a coordinator node at a given tier level. It includes the northbound part of the interface between the super-tier above the subject node and the southbound interface to the tier below, as well as the intra-tier peer-to-peer interfaces.

In addition to the cut sets, definition of the interface standards requires an understanding of data flow patterns. There are only a small number of data flow patterns that arise from the underlying mathematics of the framework. These may be seen in formulations of various control problems[34,35] for networking and electric grid operations. The patterns include:

- Hub-and-spoke flow between master and slave nodes
- Intra-tier peer-to-peer flow (one to one)
- Intra-tier peer broadcast (one to many)

Each of these flows has specific dynamic characteristics, making the application of behavioral security feasible. In addition, coordination information flows originate and terminate within the same tier pair, so that no aggregation occurs moving up the tiers, thus providing communication scalability of the framework.

Note that the regular structure of the Laminar Coordination framework makes the identification of interfaces especially simple. The primary value of the cut set exercise in this case is to group interfaces into a few classes so that interface standards and designs do not have to proliferate excessively.

3.3.12 Distributed Intelligence Computational Structure

The coordination framework must be supported by a distributed computation and communication architecture that connects centralized functions to the decentralized grid and extra-grid elements. This means that computational capability must be provided at various grid locations. In the communication networking world, this concept is known as "places in the network." A number of specific locations have been proposed for processing capacity, including in the substations,[36] at the electric meters,[37] and at various locations on distribution circuits.[38] In addition to the issue of where to locate computational capacity, there are other needs to be addressed:

- Remote device management, firmware management, address management, etc.
- Zero touch deployment
- Remote application monitoring and management

[34] Daniel P. Palomar and Mung Chiang, Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications, IEEE Transactions on Automatic Control, Vol. 52, No. 12, December 2007.
[35]Na Li, Lijun Chen, and Steven Low, Optimal Demand Response Based on Utility Maximization in Power Networks, available online at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6039082&tag=1
[36] J. Taft and M. Seewald, Developing a Distributed Intelligence Architecture for Smart Grids, CIRED 21st International Conference on Electricity Distribution, June 2011, Frankfurt, Germany, available online at http://www.cired.net/publications/cired2011/part1/papers/CIRED2011_1284_final.pdf
[37] Brian Seal, EPRI, Open Interoperable Advanced Metering, EPRI ICCS European Engagement Summit, April 2015, available online at: http://smartgrid.epri.com/doc/ICCS_Summit/I3.1_Seal_Open%20Interoperable%20AMI.pdf
[38] S. Laval and B. Godwin, Duke Energy, Distributed Intelligence Platform (DIP) Reference Architecture, Vol. 1, available online at www.duke-energy.com/pdfs/dedistributedintelligenceplatformvol01.pdf

- Device and network cyber and physical security

Figure 3.17[39] shows an example of a combined processing and communications structure for distributed intelligence in electric power systems. In this diagram, various scales of computing capacity are located at key points in the power delivery chain, including traditional operations centers, substations, locations on feeders, etc.

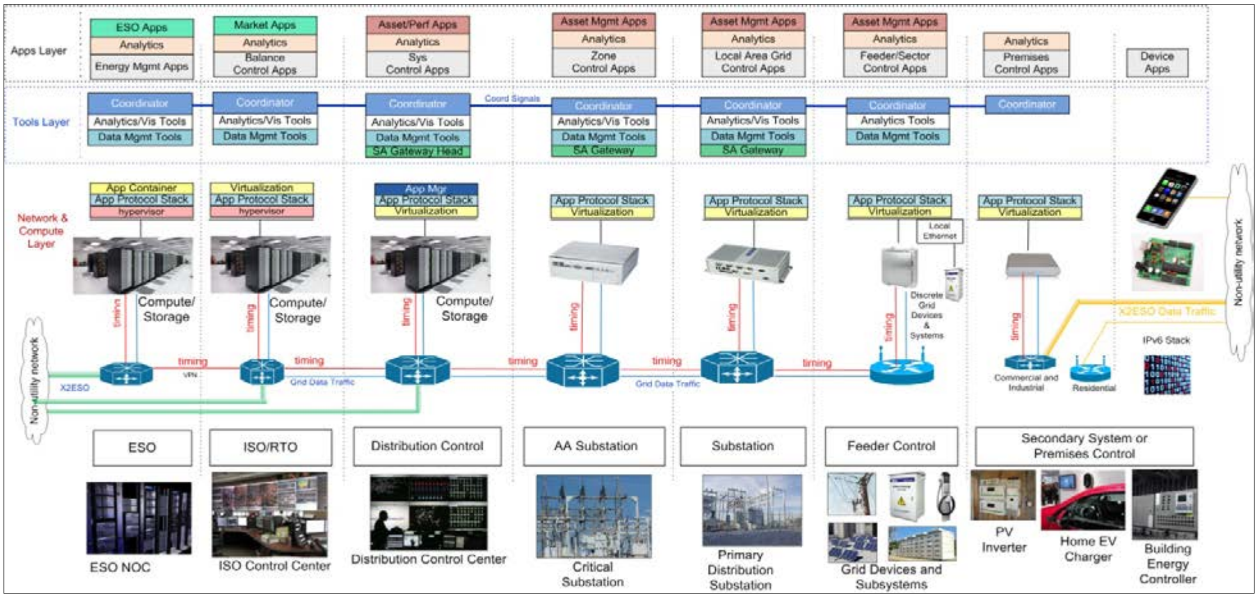

Figure 3.17. Computational and Communication Framework for Grid Distributed Intelligence

3.3.13 Summary

The Laminar Coordination framework derives from a rigorous basis in the mathematics of structure decomposition for distributed system coordination. This structure supports multi-scale systems coordination regardless of the underlying physical system structure. The mathematics also indicates the need for a particular component: the coordination node. This is essentially an optimization engine that is distributed throughout the coordination framework (noting that the nature of the optimization being performed at any particular point may differ from that being done at other points).

The coordination node has two parts: a north facing part that acts as a slave optimizer for the decomposition layer master above it, and a south-facing part that acts as a master for a decomposition layer below it. The information flow models that derive from the mathematical formulation indicate not only north and southbound flows but also potentially intra-tier flows among the coordinator nodes at a given level. The method of cut sets identifies a small group of interfaces for specialization of open interoperability standards. This greatly reduces the effort to standardize interfaces, and similarly reduces system integration costs in practical system implementations.

Using the Laminar Coordination approach, explicit coordination frameworks can be implemented for any grid, regardless of the mix of new and legacy systems and devices.

[39] This diagram is adapted with permission from Cisco Systems.

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With proper formulation and layered decomposition, the Laminar Coordination method can provide the framework for market-control/coordination of the distribution assets and the DSO/ISO interface, thus providing the mechanism to facilitate high penetration of DERs in a standardized way that takes control considerations into account. In other words**, Laminar Coordination can be the basis for the *Transactive Grid Code* for DER integration**.

Multi-layer or multi-resolution coordination frameworks can be applied at any scale and for a wide variety of grid and control structures, including conventional grids, microgrids, and networks of microgrids (sometimes called fractal grids but more accurately viewed as cellular microgrids).

3.4 Sensing and Measurement Architecture

This section addresses architecture for grid sensor networks, with primary emphasis on distribution grids. It provides background on sensing and measurement for power grids, enumerates key principles for sensor networks, describes a forward-looking view of sensor network architecture for advanced distribution grids, and discusses observability strategy and sensor allocation optimization.

3.4.1 Sensing and Measurement Basic Principles

Utility measurement and control systems and data processing systems have largely been centralized in nature. Grid control systems typically reside in control or operations centers and rely upon low complexity communications to field devices and systems. There are a few distributed control systems for utility applications, including wireless mesh systems for performing fault isolation using peer-to-peer communications among devices on feeder circuits outside of the substations. In addition, certain protection schemes involve substation-to-substation communication and local processing. In general, however, centralized systems are the rule for electric grids. Both utilities and makers of various grid control systems have recognized the value of distributed intelligence, especially at the distribution level. We define *decentralized intelligence* as the embedding of digital processing and communications in a physically dispersed, multi-element environment (specifically the power grid infrastructure but physical networks in general) and *distributed intelligence* as decentralized intelligence with the added capability of cooperation among the decentralized elements on common problems. The additional element has implications not just for algorithms, but also for communication network architecture. In the area of sensing, measurement, and data acquisition, key issues are:

- Observability and system state – key concepts that can be used to guide the design of sensor systems for physical systems with topological structure and system dynamics
- Sensing and measurement – sensor types and key characteristics; smart sensing and meters as sensors
- Data acquisition – collection of sensor data, sensor data transport
- Communications for sensor networks

These considerations and the increasing complexity of modern power grids lead to the conclusion that the electric utility engaged in grid modernization must consider creating an *observability strategy* to guide the implementation of sensing for modern grid operation. Such a strategy must, as always, draw upon the detailed knowledge of the system in question on the part of the engineers who know it best. But it must also apply tools and concepts drawn from control theory, communication networking, sensor networking, optimization, and recent developments in sensing for power grids to develop a systematic approach to providing the needed measurements in a cost-effective and manageable way. Ultimately, such a technical tool would help address risk associated with investment in sensing and measurement as part of the grid control architecture.

3.4.2 Terminology

Before delving into sensor issues, we define some basic terminology in Table 3.1 below.

Table 3.1. Basic Sensing Definitions

Term	Definition	Comment
Transducer	Generally, any device that converts one form of energy to another, but practically a device that converts some form of energy into an electrical signal or vice versa	Technically, transducer includes sensors as well as control devices (see below for definitions), but in normal usage only applies to devices that convert energy to signals or signals to control actions; in this paper we shall use transducer in the sensing context only
Sensor	A device that converts a physical quantity into an analogous signal, generally for purposes of measurement and control; includes one or more transducers along with any necessary excitation and compensation for physical influences such as temperature or humidity variations.	Most often a sensor converts some physical quantity, say, temperature, into a voltage signal that behaves in a manner analogous to the physical quantity. Sensors may be simple an inexpensive (a few cents) or complex and expensive. Some sensors are passive whereas others require energy for excitation in order to operate. Real sensors have non-ideal behaviors that often require compensation and correction.
Smart sensor, aka Intelligent Sensor	A basic sensor, combined with analog-to-digital conversion, local computation capability, and a communication interface; may also be called a digital sensor	Most smart sensors are a combination of a simple sensor and a microprocessor or microcontroller; however smart sensors can be quite elaborate and expensive.
PMU	Phasor Measurement Unit – a device for measuring and transmitting current and voltage phasors that have been acquired in a time-synchronized manner	Synchronization is typically via GPS timing; devices stream data in a manner somewhat like video; presently used on transmission systems but use at the distribution level is emerging
Meter	Technically, meters measure flow, whereas gauges measure differences (pressure, voltage, etc.). In practice electric meters measure power flow and integrate to report energy usage, but may also report voltage since this is needed to calculate power flow.	Meters use metrology boards with built-in calibration, although the actual computation algorithms are generally not made public. Meters could be thought of as smart sensors but should not be viewed as a good model for smart sensors in general.
FCI	Faulted Circuit Indicator	Feeder sensing device that detects the passage of a fault current and provides an event notification or status flag.
FDR	Frequency disturbance recorder – measures system frequency, which is a key system stability indicator	Device that monitors AC line frequency, usually at the user power outlet level.

3.4.3 Observability and System State

One view of observability is that it is temporal, geospatial, and topological awareness of all grid variables and assets. Such a definition is intuitive, but does not give us much in the way of analytical tools to work with for developing a grid measurement system. A more formal definition of observability is the ability for any combination of system state and inputs to determine the system state in a finite time using only measurement of system outputs.[40] For linear systems, knowledge of a system model enables one to calculate the observability of the system. For linear systems with known state models, the deterministic state estimation process is known as a Luenberger observer.[41] Some control engineers prefer the term estimator for this because to them the term observer tends to imply direct measurement of states. For the stochastic problem with random noise in both states and measurements, under linear quadratic Gaussian assumptions, the observer is known as a Kalman filter.[42]

For electric transmission systems with known or assumed models, a snapshot-based process using a set of sparse state variable measurements, a system model, and a mathematically intense solution method (weighted least squares, linear programming, Newton-Raphson iteration, etc.) performs what is widely known as transmission *state estimation.*[43] State estimation for distribution grids involves a number of complications that do not exist at the transmission level. These include the fact that distribution circuits operate almost always in a time-varying unbalanced mode so that estimates must be made for all three phases independently, actual connectivity may be poorly known so that models typically used in state estimation would not be sufficiently accurate to use the results, and circuit-switched configuration changes can change topology in between the time of a state estimate and the time that actions based on that estimate are taken. Consequently, it can be helpful to rely more on state measurement and less on state estimation in the distribution case whenever we can arrange for the necessary instrumentation. The need to provide grid state for control purposes leads to the need for observability and therefore sensing and measurement architecture.

State is the minimum set of values (state variables) that describe the instantaneous condition of a dynamic system. State variables may be continuous (physical systems), discrete (logical systems and processes), or stochastic. For many types of systems and for linear systems in particular, the mathematics of state are well defined in the context of differential equation solutions of system dynamics. State has the property that future state of a dynamic system is completely defined by the present state and system inputs only. Knowledge of past state trajectory or past inputs is not necessary.

For stochastic variables we may employ the concept of stochastic state as embodied in (possibly hidden) Markov models, where the observed statistical behavior relates to an underlying stochastic state model.[44] A Markov model is a state model where transitions from state to state are described by probabilities rather than deterministic dynamics. The Markov model concept is a useful way to include power quality as an element of grid state.

The concept of state applies equally well for logical systems with discrete states. The open/closed or on/off states of switches are prime examples; state transition diagrams and matrices are used to describe discrete system behavior. Logical systems are often described by state transition diagrams but these can be converted to discrete state transition tables,[45] analogous to state transition matrices used in dynamic system formulations for modern controls.

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[40] G. Franklin, J. D. Powell, and A. Emani-Naeini, Feedback Control of Dynamic Systems, 6th Edition, Pearson Higher Education, Upper Saddle River, NJ, 2010.

[41] D. G. Luenberger, Observing the State of a Linear System, IEEE Transactions On Military Electronics, MIL-8, 1964.

[42] Andrew P. Sage and Chelsea C. White III, Optimum Systems Control 2nd Ed., Prentice-Hall, New Jersey, 1977.

[43] M Filho, et. al., Bibliography on Power State Estimation (1968-1989), IEEE Transactions on Power Systems, August 1990, pp. 950-961.

[44] Jia Li, Hidden Markov Model, The Pennsylvania State University, available online: sites.*stat.psu.edu/~jiali/course/stat597e/notes2/hmm.pdf.*

[45] Frederick J. Hill and Gerald R. Peterson, Switching Theory and Logical Design, 2nd Edition, John Wiley and Sons, New York, 1974.

For power grid observability, we find it useful to use an extended distribution grid state definition, where we augment the VfPQ (voltage, frequency, real power, reactive power) view of grid power state with additional elements, such circuit parameters, storage charge state, DER available capacity and technical losses. We can calculate circuit section impedance values from online measurements during the grid state determination process, for example. When grid state is fully determined, we may then use it to define other grid conditions of interest.

For power grids, *extended state* is a collection of variables that fall into six categories, plus a set of adjuncts in the form of forecasts and various derived quantities of interest. Figure 3.18 illustrates a taxonomy of extended grid state elements.

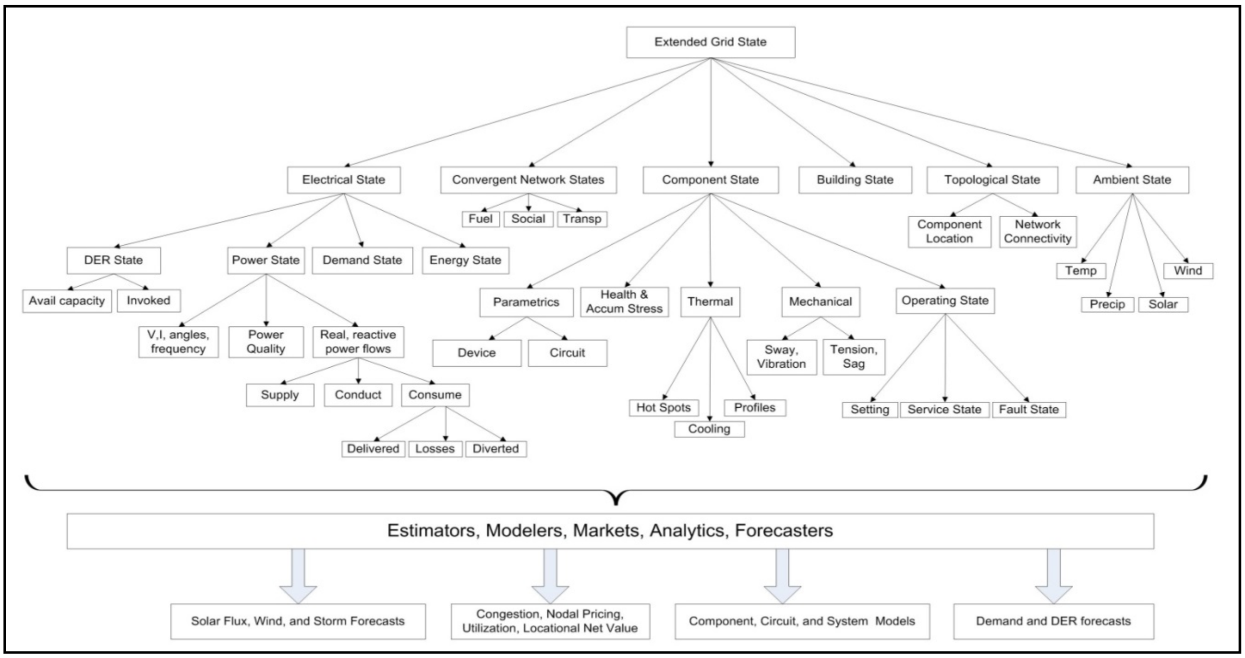

Figure 3.18. Grid State Elements and Derived Quantities

The six primary grid state groups and adjuncts are:

Electrical State – the extension of power state to the entire extended grid (transmission, distribution, and prosumer domains); includes standard power state, energy state for storage, instantaneous demand, and DER available capacity and invoked capacity.

Component State – instantaneous condition of grid components, including value of model parameters, component health, thermal state, mechanical state (e.g., cable tension and sag), and operating state (in or out of service, setting or set point, fault condition, etc.).

Topological State – connectivity of grid networks (electrical, communications, control and coordination); also includes topological location of connected grid and prosumer components which are crucial for planning and control.

Building State – not strictly part of grid state but useful for both building control and for grid interface in building-to-grid applications.

Ambient State – also not part of grid state but these exogenous factors (solar flux, wind, precipitation, etc.) are closely related to grid operation and control and so are included in the extended grid state definition.

Convergent Network States – As indicated in the Grid Architecture work, various other networks have or are converging with grids, necessitating availability of state variables for these networks as part of extended grid state.

Estimators, Modelers, Markets, Analytics, and Forecasters – a variety of elements that are not state variables but are nonetheless important to modern grid operation are produced as the output of a variety of tools and applications. These elements, such as wind, solar, and DER availability forecasts, congestion, locational marginal prices, etc., are often driven by both grid state variables and measurements used to derive grid state. Forecasts are extremely important because many of the systems and devices used in the grid have dynamics of their own (ramp rate, etc.) and cannot react instantly to control commands. Other resources require advance notice to be available for use.

Since knowledge of grid state is fundamental to most grid control and management applications, determination of state is vital.

We use the term grid state *determination* (as opposed to estimation) for the process involved on a power grid, since we may measure some grid power states directly, or we may make measurements from which state elements can be calculated or estimated, or we may use a mix of measured and estimated states. In the case of power grids, we want to know the grid state on a moment to moment basis, since this information is the foundation of many smart grid functions and capabilities. Determining extended grid state is a multi-stage process, comprising:

- Sensing, measurement and data acquisition – the basic processes of obtaining raw grid data, with conversion from analog to digital form
- Filtering, linearization, scaling, and units conversion – conversion and processing of raw digital data from uncompensated integer counts to compensated, linearized values, scaled to engineering or physical quantity units as opposed to dimensionless integers
- Representation – conversion of physical variables into forms suitable for analysis and use in control in any of several domains: time, frequency, geospatial, or electrical distance from a reference points such as a substation
- State formation – construction of actual grid state elements; may involve several computational processes such as extraction of parameters from data sets, estimation where necessary, and then assembly of grid state elements
- Distribution and persistence – grid state elements must be made available to various decision and control processes, and may have to be persisted in any of several tiers of data storage, depending on the various uses for the data

Aggregation may occur at several levels. Note that by aggregation we mean the summarization of data, resulting in *reduction* of data volume, as opposed to the communications networking meaning of aggregation, which is the accumulation of data flows that results in an *increase* of data volume. As an example of grid data aggregation, raw instantaneous voltage or current samples may be collected into records so that they can be summarized into Root-Mean-Square (RMS) values, harmonic content measures, and a few other parameters. If we have meters that can measure real and reactive power, we can aggregate values to determine power flows at various points on a feeder. We may aggregate current and power flows from points to feeder segments to feeder sections, to substations, to transmission lines, to service areas to control areas.

We may characterize state in various ways by representing state variables in any of four domains: time, frequency, geospatial, and electrical distance and may calculate various metrics to assist in extracting meaning from state variables (example: calculating power factor from real and reactive power). Transforming state variables in various ways reveals information (example: converting phasors to symmetrical components) that make implementations of various grid applications straightforward.

The concept of grid state is extremely useful for advanced grid data management and control. Consequently, the determination of grid state is a crucial advanced grid process. Due to the complexity of distribution grids and the cost of sensor installation, implementing proper grid state determination is not a trivial exercise. For each feeder, we must create a grid sensing strategy that, when applied across the whole system, results in a sensor network design for the entire grid. The strategy is necessary to ensure that sufficient measurement is done to provide grid state determination, while minimizing the total cost of the sensor network (including not just material costs but also installation and service labor).

The complexity of modern grids is such that real concerns are arising about the limits of observability. Coupling through the grid complicates the observation process, but more importantly, unstructured additions to power grids can cause a degree of architectural chaos that makes the determination of grid state a challenge. This lack of structure, combined with severe complexity, appears to place limits on achievable observability. This problem can be combated by regularizing grid and control system structure so that it is not prohibitively expensive to provide the sensing and data processing necessary to achieve the observability required to drive decision and control.

3.4.4 Sensing and Measurement for Power Grids

Power grids use a wide array of sensing devices, including sensing built into grid control devices, as well as explicit sensors. A key tradeoff for sensor network design has been the use of many low costs sensors (example: Faulted Circuit Indicators or FCIs) vs. the use of a smaller number of high end sensors (example: multi-variable line sensors). At the highest end sensor are the phasor measurement units (PMUs) used on transmission systems to provide synchronized phasor measurement, but which are being introduced at the distribution level now. As modern grid complexity increases, the move toward synchronized measurement necessitated by advanced control requirements leads to the use of high end sensors on distribution feeders. Despite this trend, it is still valid to consider the use of low end sensors and in the more sophisticated approaches, to employ a mix of sensor types. Part of the observability strategy issue is to determine the mix of sensors to be used for a particular system. Smart line sensors and advanced meters are two logical options for distribution grid power state sensing.

A smart sensor is one that contains a physical parameter transducer, means to convert analog sensor signals to digital form, a digital processor, with memory, embedded software, possibly downloaded applications, and digital communications capability.

The typical configuration of a distribution power line electrical sensor would use three signal channels for phase voltage waveform measurement, three channels for phase current waveform measurement, one channel for neutral current measurement, and one channel for temperature measurement. Voltage and current waveforms should be sampled at 128 or more samples per cycle.[46] Signal channels must include analog anti-aliasing filters. Simultaneous sample/holds are preferred because some processing functions are concerned with relative phase.

[46] IEEE Std 1159-2009 IEEE Recommended Practice for Monitoring Electric Power Quality. Available online.

The smart sensor platform must contain at least one digital processor with sufficient processing capacity and memory to support local data acquisition, digital signal processing, and digital communications. This platform must be capable of receiving downloaded applications and of performing bi-directional communications over various communication media and with various protocols. It must provide data security functions including:

- Encryption – encoding of data in such a way that only authorized receivers can read it
- Identification – provision of information to differentiate an entity from all others
- Authentication – the process of actually confirming an identity
- Non-repudiation – association of actions or changes to a unique entity
- Tamper detection/prevention – physical and firmware integrity

The smart sensor should support standard protocols for network routing, timing (IEEE 1588[47]), and management (SNMP[48] for example).

It is useful for the sensors to support Transducer Electronic Data Sheets (TEDS),[49] to provide management of sensor –specific information so that multiple data collection engines or controls can access the sensor without need to access a central data collection system to obtain calibrated data. At the upper end of smart line sensor capability is the distribution level PMU, now being called the microPMU. Besides the issue of cost, microPMUs differ from transmission PMUs in that they must be usable outdoors on utility poles and must have extremely accurate phase measurement capability, so that they can measure small phase shifts along a feeder section. At the lower end are binary sensors such as fuse state monitors and faulted circuit indicators, which generally signal (mostly) rare events, as opposed to providing telemetry streams.

When a utility has or will be deploying an Advanced Meter Infrastructure (AMI) system, it is logical to consider how this meter system may be used as a grid sensor network. Many residential meters are capable of sensing and reporting secondary voltage in addition to usage data. Newer Commercial and Industrial (C&I) meters have significant capabilities for measuring and reporting real and reactive power, power factor, voltage sags, and harmonics in voltage and current.

When an AMI system is in place, careful selection of meters that are approximately evenly spaced along a distribution feeder (in terms of distribution transformer electrical distance from the substation) should enable the determination of feeder voltage profiles, which would be valuable in voltage regulation. In addition, instant voltage readings ("pings") should enable rapid determination of outage extent and restoration progress. Rapid voltage reading could also enable operational verification for grid devices such as switched, reclosers, and capacitors, by providing voltage values just before and just after device command issuance. Those meters that can record voltage sags or compute harmonics in power waveforms can be used to measure power quality state elements. All of these functions have in fact been tried with AMI and C&I meter systems.

In practice, residential meter systems have not proven to be the all-encompassing sensor fabrics for power grids that many have desired them to be. There are several reasons for this:

[47] IEEE Standards Association, IEEE Std 1588 – Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, 2011, available online at http://standards.ieee.org/findstds/interps/1588-2008.html .

[48] Simple Network Management Protocol

[49] NIST, IEEE P1451 Smart Transducer Interface Standard, see http://www.nist.gov/el/isd/ieee/ieee1451.cfm, and available online at http://www.ieee.org/index.html .

- 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 measurements are not made in a useful manner
- Meter communication networks have often been designed only to support usage reporting and so do not have the bandwidth and latency capabilities to support operation as a grid sensor network; this means that the meters cannot provide sensor-type data fast enough to be useful for any but the slowest (read: old style) distribution automation control systems
- Meter communication protocols until recently did not support sensor-like operation, having been developed from a usage reporting point of view; consequently, it is normally necessary 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 often the relationship to power grid connectivity is not well documented; 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
- Wireless mesh-based meter communications networks are “lossy”, meaning that they are unreliable in terms of message packet delivery which is not a severe problem for usage reporting but is a severe problem for control system support
- Some 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

For meters to be useful for any but the simplest distribution automation functions, these issues must be remedied. This means, reliable communications, efficient communication protocols and interfaces, support for time synchronization via IEEE 1588-time service, synchronized sampling capability, and sensor-grade measurement functions for more than just energy usage.

3.4.5 Data Acquisition

Power grid devices and sensors operate in one or more of five data acquisition modes:

- Polling – a polling master queries the device or sensor, which responds with the most recent values of the specified data points; polling is usually on a regular schedule and data size per query is modest
- Report by exception – the device or sensor pushes a data value to the master when the data changes by a specified amount
- Streaming – the sensor sends a continuous stream of data, once streaming is initiated, until streaming is terminated by command or abnormal exit condition
- Interrogation of stored files – the device maintains a log or data file; upon query, it transmits the log or file to the master; differs from polling in terms of data size per query and frequency/regularity of the query
- Asynchronous event message – the device uses internal processing to detect a specific condition indicated by the data and spontaneously sends an event message to the master or any subscribing system- the message may or may not contain actual sensor data relevant to the event; the internal

event can be a clock signal or countdown so that the messages are sent on a regular basis, but initiated by the sensor, not a central controller

Polling is common in grid control systems, but report by exception is used in some systems to reduce data volumes and therefore communication line bandwidth. Streaming is common for advanced sensors such as PMU-based wide area measurement systems (WAMS). Interrogation of stored data files is common for meters and for data loggers and grid devices that collect records on a power waveform event-triggered basis. Asynchronous event messages are becoming more common in devices that contain significant local processing and are therefore able to detect and report events.

Collection of the data in large scale systems such as advanced power grids presents issues of cycle time, data bursting, and sample skew. In the typical round-robin scanning approach taken by many standard SCADA[50] systems, the time skew between first and last samples represents an issue for control systems that is insignificant when the scan cycle time is short compared to system dynamics, but as dynamics in increase in speed (such as with advanced regulation and stabilization), and as the number of sensing points increases, the sample time skew problem becomes significant. This is fundamentally a scaling issue.

In a control system where distributed endpoints are free-running and each is updating its measurement(s) asynchronously, round robin collection of the data can result in time skew among samples. This can cause a degradation of accuracy in creating state estimates from the data samples, with resultant degradation of control performance

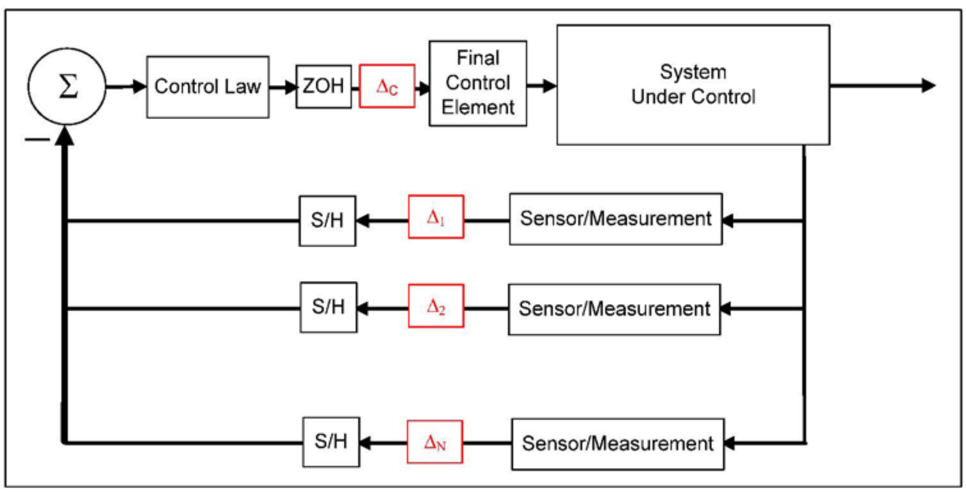

Figure 3.19. Multi-Sensor Sample Skew Model for Closed Loop Control

For many control systems, especially those used in power systems, multiple sensors provide data from widely separated locations. Figure 3.19 shows a model for multiple measurement delays, plus a control output delay. In this model, multiple sensors provide feedback from the system being controlled to a controller. Each sensor has a separate and potentially different time delay. In addition, the control command may also experience another delay when transmitted to a control element. This last latency is why remote closed loop control is not feasible in some cases.

In a control system where distributed endpoints are free-running and each is updating its measurement(s) asynchronously, round robin collection of the data can result in time skew among samples. This can cause

[50] Supervisory Control and Data Acquisition

a degradation of accuracy in creating state estimates from the data samples, with resultant degradation of control performance. The skew model is needed when dealing with SCADA and with controls that need multiple sensor feedback inputs. An example of the latter is using two PMUs as input to a power electronics controller for modal power oscillation damping on transmission systems.

In practice, sensors should perform synchronized measurement and the data acquisition system must be capable of collecting all of the samples in a time window short enough to be completed before the next sampling cycle begins. This becomes increasingly difficult as the number of sensing endpoints increases.

In the next section, we provide a brief discussion of networking issues for sensors. This is a subset of general networking architecture for power grids.[51]

3.4.6 Distribution Grid Topological State (Electrical Connectivity) Representation

Distribution grids present special problems in terms of topological state. Such state information is crucial because it is the context in which grid data, events, and control commands must be interpreted. The problems arise because unlike transmission grids, "as-built" topology for distribution grids is often not completely or accurately known. In addition, distribution grid topology can be dynamic, such as in the cases where feeders are partially meshed or are tied to other feeders for reliability reasons. In such cases, circuit switches, sectionalizers, or reclosers may be operated to change the topology and such changes can be frequent. Consequently, flows in a given circuit section can reverse, as can voltage rises and drops. With the advent of Distributed Generation (DG) penetration on distribution feeders, power flow reversals and loops can occur, impacting protection and Volt/VAr regulation.

Due to grid switching, a feeder section may "belong" to more than one feeder or substation. This raises several issues: how to obtain real time circuit topology, how to represent power state for such sections (since power state must refer to circuit topology), and how to handle distributed sensor data acquisition (which of the several distributed DCEs should collect the data from a section that can belong to more than one substation, for example – note that the sensor network approach described below resolves this last issue neatly).

The issue of circuit topology determination is one of the hidden issues for distribution grid design, because it can undermine many of the advanced capabilities that modern grids are intended to achieve and yet the issue is often not discussed or included in the sensor system design process. Furthermore, it is not sufficient to have topological state on a current operational data basis (meaning the present value). This is because data may not always be interpreted or acted upon immediately. If there is a process delay, circuit topology may change in between the time the data or event message was generated and the time when the data is processed or the time that a control command is issued. Therefore, past values of topological state are needed in order to provide the correct context for the data, whereas present or possibly even future values are needed to provide context for control commands.

One method of providing the multiple versions of topology that are needed for advanced grid control is to capture the state changes of grid switches, reclosers, sectionalizers, and inter-ties in a time series database and then use a topology processor to reconstruct topology for any required present or past time. The collection of these state transitions is often problematic because the switching device may not report back its state and also because the device may malfunction. In addition, not all switching devices are automatic – many distribution grids contain large numbers of manually-operated switches. Capture of state

[51] J. Taft, et. al., Cisco GridBlocks Architecture: A Reference for Utility Network Design, Cisco, April 2012, available online at http://www.cisco.com/web/strategy/energy/gridblocks_architecture.html .

transitions for such devices is problematic, but can be resolved with a degree of line sensing designed to provide measurement of power state variables that allow automatic inference of the switch state transitions (by sensing changes in line voltage or current flow). If switch state transition determination is an issue, then an aspect of observability strategy should be to include means to sense those changes.

3.4.7 Communications for Power Grid Sensor Networks

Communication networks are crucial elements of modern grids, and can help or hinder, depending on the nature of the communication technology and the advanced grid functional and performance requirements. Among the key parameters are:

- Bandwidth
- Latency
- Burst response
- Average throughput as a function of number of endpoints
- Network structure
- Reconvergence time after a fault or outage

Bandwidth is the obvious criterion, but quite often bandwidth requirements are underestimated due to a lack of understanding of the analytics and applications that will make use of data being transported from sensors to usage points. The most common mistake is to ignore data and analytics associated with the high end sensors that may be used in a modern distribution grid. These sensors and the applications that use them involve much higher bandwidths than traditional SCADA sensing points, as they produce significant data on each power cycle (20 msec in Europeans style grids, 16.67 msec in North American style grids). Such devices can produce more data flow per feeder than the meters or any other sensors. In some control architectures, this data must flow to the substations for processing and consumption rather than to a control center; hence the per-feeder consideration.

Substations are another major source of high data rate flows due to the number and sophistication of the sensors they can contain. Depending on the number and kind of devices involved, substations may have bandwidth requirements that range from 64 kbps to as much as 50 Mbps. Data may flow to control centers or to peer substations.

Latency matters because some advanced grid functions and therefore analytics are “real time”, meaning that the results must be produced from newly sensed data and delivered for action within strict time constraints. The bounding latency may be as little as a few power cycles for the fastest functions; it may be a dozen cycles for slightly slower functions; it may be sub-second, or sub-minute for others; finally, there are analytics for which the bounding latency is so large that for all practical purposes they are not “real time” at all. Some communication networks have more than sufficient latency performance for grid data and analytics, but have excessive latencies. This is usually due to the network having a multi-hop implementation, something that is very common in wireless mesh networks. This issue is also a problem with some Power Line Communication (PLC) and most Broadband over Power Line (BPL) systems.

Burst response matters because many advanced grid devices produce data in bursts and floods, rather than in steady streams. Such bursts occur in response to faults and outages, for example. They can be generated by smart meter systems due to momentary voltage sags on feeder circuits and then again in response to restoration of normal voltage, for example. A communication network that has sufficient bandwidth for steady state data flows can lose data due to buffer overflows during data bursts. Since the bursts in a modern grid system usually occur when something critical is happening, loss of such data can constitute a crucial grid failure.

Average throughput as a function of the number of endpoints matters because modernized grid systems are built incrementally in the US and are incrementally loaded with new endpoints. A network that provides adequate bandwidth and latency initially can become unacceptable as endpoints are added (this is especially a hazard for networks initially designed to carry AMI traffic, and then re-purposed to carry distribution automation traffic in addition to the original AMI load). The reason is that there is a threshold effect for average response time that causes the network performance to degrade dramatically when the "knee" of the average throughput curve is reached by increasing the number of endpoint devices using the network. As the number of endpoints increases, the average time to deliver messages increases, as does the amount of queuing necessary to prevent message loss.[52] This delivery time effect is illustrated Figure 3.20.

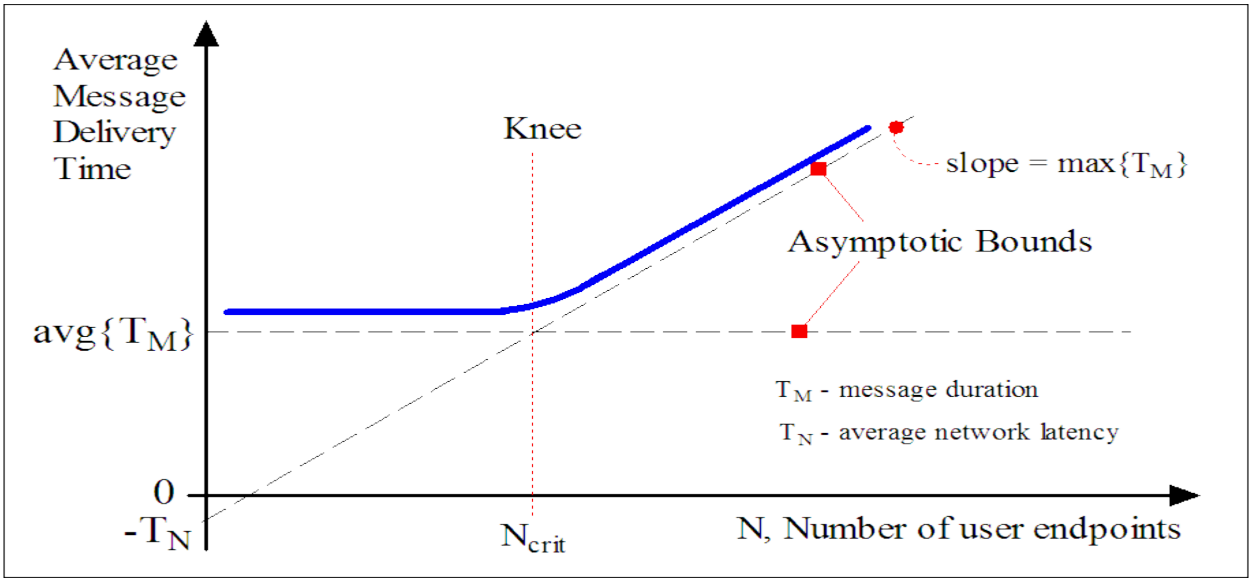

Figure 3.20. Average Message Delivery Time Knee Effect

Additional factors to be considered for wireless networks include coverage and, in the case of wireless mesh networks, re-convergence. When a wireless mesh network is disrupted, by say, a power failure, it must re-converge to a configuration that allows message packet forwarding. Some mesh networks re-converge slowly, and worse, some have problems re-converging at all under pathological topologies. Such topologies are the result of the mesh network physical layout and can occur unpredictably. Even without pathological topologies, mesh networks may have unacceptably long re-convergence times due to excessively long beacon intervals and other internal settings.[53]

Ultimately, the characteristics of the communication network must be taken into account when developing the observability strategy. If the communication system is legacy, then it may well place limits on observability. For that matter, a new communication network may do the same. When network bottlenecking is a significant possibility, alternatives include:

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[52] Raj Jain, Art of Computer Systems Performance Analysis Techniques for Experimental Design, Measurements, Simulation And Modeling, Wiley Computer Publishing, 1991.See Chapter 33, available online at http://www.scribd.com/doc/86318410/231/CHAPTER-33-OPERATIONAL-LAWS

[53] J. Taft and A. Becker-Dippmann, The Emerging Interdependence of the Electric Power Grid and Information and Communication Technology, available online at http://www.osti.gov/scitech/biblio/1221500

- Data compression at the point of measurement or elsewhere in the data transport path
- Use of distributed analytics to extract and preserve information while reducing data volume

As a matter of good network architecture, the communication network core should be kept free of application devices. Such devices must be kept at the edge of the network and the use of protocol converters must be minimized and kept to the edge of the network as well. It is far preferable that the edge devices be capable of supporting the same communication protocol stack as the core, but for many legacy devices this is not going to be the case. This core/edge principle also applies to concentrators and other "over the top" devices that would superimpose a secondary network on top of the core network. Concentrators, where needed, must be located at the network edge, and must not be stacked (concatenated). The "core and edge" and the "network of networks" structures are the basis of the internet and are largely responsible for its scalability.

The consequences of these approaches are increases in the computation power at endpoints, potential additional data security issues, and new requirements for management of distributed software and smart devices.

3.4.8 Sensor Network Architecture Principles

Sensor system architecture is a subset of grid architecture that cuts across electric infrastructure, ICT networks, control and coordination structures, and data management structures. Grid sensors have generally been associated with specific systems or applications and have been deployed as adjuncts to those systems or applications. Consequently, they have not generally been treated as network structures with architecture and relevant standards. It is helpful to start off viewing sensor and measurement systems abstractly in a layer format, as shown in Figure 3.21 below.

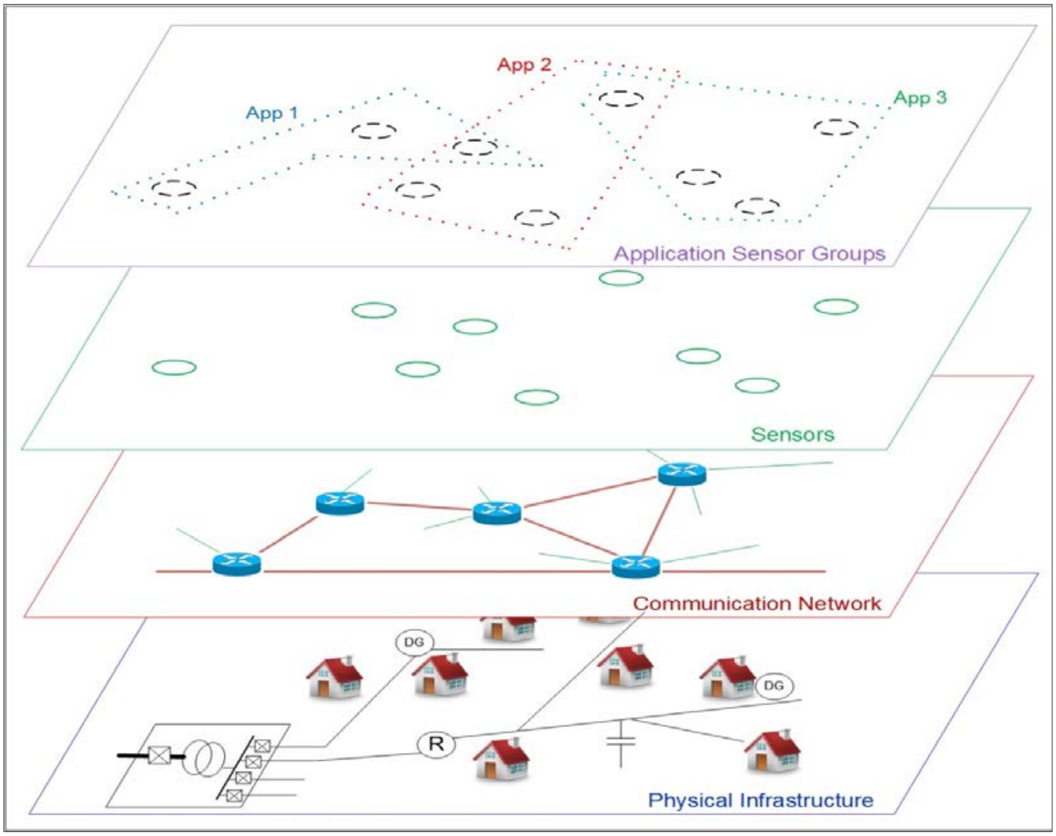

Figure 3.21. Sensor Architecture Abstraction Layer Model

Sensor network architecture must consider the underlying physical system structure, the relationship to communications network, and the relationship or relationships to applications that make use of sensor data. As with other grid architecture work, these structures should be considered together, especially in the case where new communications networking is being developed along with the other structures, as would be the case in much distribution grid modernization. Legacy components and structures must be considered as constraints and as potential assets in the architecture development and subsequent design processes.

In most grid systems, sensors are rigidly bound to specific applications or systems and usually form non-overlapping sets. It is these silos which are the source of the essential limitations that are addressed below. In the sensor network architecture approach this constraint can be relaxed so that sensors may not only form application-specific groups, but may do so dynamically and in overlapping sets. Such capability can greatly enhance overall grid adaptability by resolving the data access problem for applications in a manner that is more efficient and scalable than incurring the overhead and latency associated with making use of interoperability standards to transfer low level data from one application system to another.

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An advantage of the network-of-structures paradigm over the system-of-systems paradigm is that structural insights and changes fundamentally affect system limits and external properties whereas system-of-systems views focus on components and make it difficult to identify opportunities to change structure to obtain improved capability or performance.

At the architectural level, a number of additional sensor system issues must be considered that involve how sensors acquire, store, and represent data, and how sensor nodes are controlled. In the defense industry, these issues have been considered and characterized as described below.

Query modes – the query mode describes how sensors respond to data queries. The set of query modes includes:

- Scan mode – sensors are polled for simple point lists; most commonly used in utility systems (e.g., Remote Terminal Unit DNP3 slaves)
- Database mode – sensors act as a database; they support queries (requires a sensor operating system, sensor query language and/or middleware)[54]
- Active network mode – agents execute sensing tasks cooperatively[55]
  - Client/server – agents post data to a server; other agents act as clients to obtain data via the service
  - Meetings – agents exchange information in peer groups or sub-groups at specified times
  - Blackboards – common areas where data can be posted by any agent, then scanned by others for relevance

Node programming model – methods by which software/firmware is downloaded to sensor nodes

- Collectively programmed
  - Sensor middleware – requires a layer of software that consumes node resources, thus severely limiting application software size
  - Viral programming – files are passed from node to node; very difficult to ensure if and when all nodes are updated
- Individually programmed
  - Fixed firmware – rarely use as this method lacks flexibility and requires great cost to upgrade since each box must be touched
  - Remote download – widely used for meters and other devices; the issue here is both the time to upgrade a large number of devices and the cost if a service provider network with data-based tariffs is used

[54] C. Jaikaeo, et. al., “Querying and Tasking of Sensor Networks,” SPIE’s 14th Annual International Symposium on Aerospace/Defense Sensing, Simulation, Control (Digitization of the Battlespace V), Orlando, Fla, April 26-27, 2000.
[55] G. Cabri, et. al., “MARS: A Programmable Coordination Architecture for Mobil Agents,” IEEE Internet Computing, Jul-Aug, 2000, pp. 216-35.

Information abstraction model – the information abstraction model describes how much processing will be applied at the sensor level before the sensor reports outputs. The information abstraction models include:

- Send raw data samples – the simplest approach but also the highest volume data when waveforms are involved; this is used more for asset monitoring telemetry (e.g. power transformer top oil temperature) but has a key use case in differential protection, where the IEC 61850 Sample Values (SV) mode comes into play
- Send characterizations
  – Send parameters and analytics – this is widely used in smart sensors and provides a type of data compression since it extracts useful information from a body of raw sensor data (e.g. converting a set of waveform samples to RMS voltage, RMS current, real power and reactive power)
  – Send decisions and classifications – an even more compressed version of parameters and analytics reporting

Of course, it is quite possible and proper to design sensor systems that make use of more than one of these modes.

Note that for Multi-Agent Systems (MAS), grid state may be propagated via what is known in the MAS field as "belief sharing," or may be propagated by letting agents observe the actions of other agents (decisions and classifications in our case). Both methods have limitations in that each node's view of grid state gradually converges to what is expected to be correct values assuming that state is essentially static, but is known that the second method has especially severe limitations.[56] If the grid state is not static, then the dynamics of state propagation compound the dynamics of the grid and associated devices.

3.4.9 Sensor Virtualization

The term "sensor virtualization" has several usages but in this paper it means the use of software to allow one or more sensing nodes to act as one or more abstract sensors, with unnecessary physical details hidden from application software that uses the sensor.[57] In the software virtualization approach, all of the physical sensors are connected through a software platform that hides the physical details of the sensors and provides an interface to multiple applications. The software layer may run on servers in a control or data center on at the sensors themselves. Figure 3.22 shows a basic sensor virtualization platform component model.

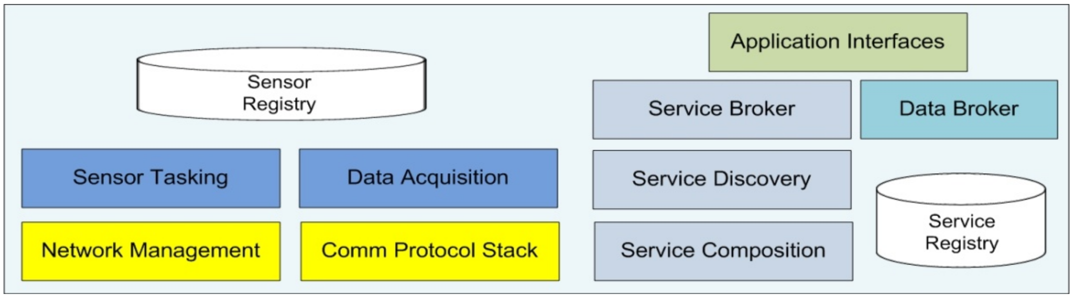

Figure 3.22. Sensor Virtualization Software Platform

[56]Petar M. Djuric and Yunlong Wang, Evolution of Social Belief in Multiagent Systems, Proc. IEEE Workshop on Statistical Signal Processing, Nice, France, 2011, pp. 353-356
[57]Anura P. Jayasumana, et. al., "Virtual Sensor Networks – A Resource Efficient Approach for Concurrent Applications," IEEE Computer Society International Conference on Information Technology, 2007.

This approach aligns with another concept that has been proposed for use in grid information system design: separation of data from applications. In that model, all grid data is stored in a multi-tiered data management system, instead of being stored in siloed sets by the application systems. Each application accesses the common data store via open standard interfaces. Such approaches have actually been developed[58] but most grid system vendors have tended to retain siloed architectures but with interfaces that support interoperability standards. Disadvantages of this approach are its essentially centralized structure that does not accommodate distributed solutions well, and it has high inherent latency due to indirect access to grid data, which must pass from data acquisition to virtualization platform to data stores before becoming available to applications. The siloed approach reduces latency to the applications in the system doing the data acquisition, but adds significant latency to any other application that must request data from the system that initially acquired it. The siloed system can perform data conditioning appropriate for the applications in that system, but this treatment may not be appropriate for other systems requesting the data.

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As grid dynamics increase in speed it is necessary to consider sensor subsystem dynamics when determining control stability. Consequently, it is useful to consider architectural structures for sensors that minimize inherent latency.

3.4.10 Architecture View: Advanced Distribution Sensor Network

In this section, several of the ideas described earlier are combined to produce a view of a *sensor network* for distribution grids that eliminates the need for exchange of sensor data among application systems and provides flexibility and scalability for both centralized and distributed systems.

Traditional systems (that may employ sensor virtualization platforms or SCADA) have a structure as shown in Figure 3.23 below, which is essentially an application/virtualization platform/communication network/sensor set stack.

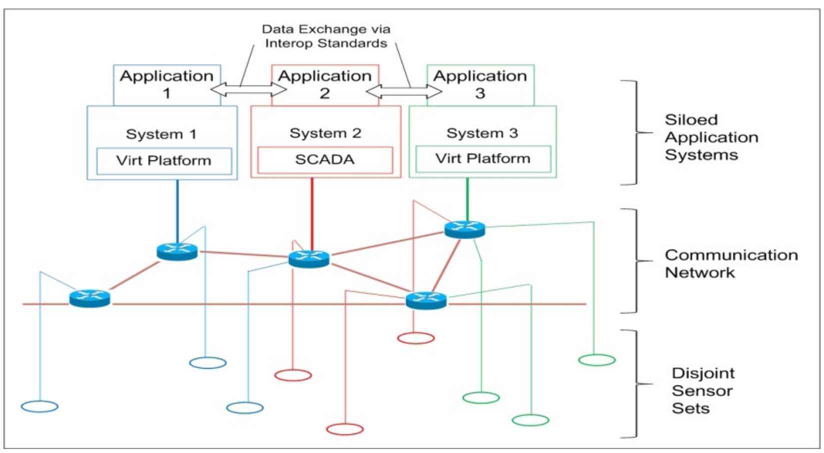

Figure 3.23. Traditional Sensor System Structure

[58] Accenture staff, Accenture Launches Smart Grid Data Management Solution, March 2010, available online at https://newsroom.accenture.com/industries/energy/accenture-launches-smart-grid-data-management-solution-to-reduce-risks-and-costs-smart-grid-deployments.htm

The core concepts on which a new architectural view is constructed are:

- Combination of streaming sensors and communications into a structure (the sensor network)
- Dynamic sensor grouping and binding
- Synchronized data sampling
- Multi-layer aggregation and distributed intelligence support
- Use of network protocols and services as integral parts of the sensor network
- Network level cyber security

Building on the concept of network-based sensor virtualization, it is possible to combine the sensors and communication networks into a single structure that provides grid data services to applications in a highly flexible and scalable manner. Given sufficient network capacity, this structure can scale to large numbers of sensors, with incremental additions requiring minimal integration effort. Due to its inherently distributed nature, it can support multiple centralized and decentralized models for application implementation, including Laminar Coordination, distributed intelligence, and multi-agent systems.

3.4.11 Basic Structure of the Sensor Network

The sensor network architectural view treats sensors and the communication network as an integrated structure. Various services are inserted into this structure and where possible the structure employs advanced communication protocols to provide capabilities often either built into siloed applications or supplied via an abstraction layer software platform. Data can flow from streaming sensors (sensors that produce continual streams of data, much like PMUs or video) to any authorized recipient application; in fact multiple devices or applications can receive such streams – applications merely need to be connected to the network at some point. In that sense, the sensor network can operate as a publish-and-subscribe data system. Such operation for sensors has been already described and demonstrated in the context of PMU networks.[59]

For sensors that do not have streaming capability, data acquisition engines may be attached to the edge of the sensor network to perform more traditional polling and other modes of data collection. Hence both legacy SCADA and more distributed data collection can coexist on the same network. Similarly, distributed database data store nodes may be attached to the sensor network, or data may be accumulated into individual applications. Each application may associate sensors as needed, providing low-latency grid data access with great flexibility.

Various services can be integrated into the sensor network via attached servers or through integration into network management systems. These include standard network management and security functions as well as grid-specific capabilities such as sensor meta-data management, IEC 61850 CIM interface services, and grid topology/connectivity.

This structure can serve as a sensor data platform without the latency caused by passing through intermediate layers of software or transfer of data from one application system to another. It provides more flexibility than approaches that separate data from applications but then store the data in centralized data stores. New data sources (sensors) can be added by simple network attachment/admission, and new

[59] Cisco staff, PMU Networking with IP Multicast, available online at http://www.cisco.com/c/en/us/products/collateral/routers/2000-series-connected-grid-routers/whitepaper_c11-697665.html

users of data can access data for which they are authorized in real time without intermediate virtualization layer and application or data collection system latencies. Compare this to the typical scenario where one system collects data from a set of dedicated grid sensors, then stores the data into an internal historian, and periodically copies the data over to a "shadow" historian, which then may be queried by another application system that wants the (by then very stale) data by way of an interoperability standard that may be several layers higher in abstraction than is needed by the system requesting the data.[60]

Such a sensor network offers flexibility, low latency, and scalability but significantly changes the view about where interoperability standards should apply by decoupling sensors from application systems and coupling them to communication networks instead.

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Architectural structure can greatly change the context in which interoperability is defined. In particular, a focus on new structures instead of legacy components can completely change the nature of information interchange and thereby redefine interoperability and interoperability standards.

Architecture should be used as the contextual framework for interoperability standards.

3.4.12 Dynamic Sensor Grouping and Micro-Virtualization

Given a network of smart sensors, it is possible to have applications associate to sensor subsets in a general and flexible manner. Applications can merely subscribe to the data from the appropriate set of sensors and sensor sets do not have to be disjoint. The sensor network and the applications must have certain capabilities for this to work autonomously (it is always possible for a human network manager to specify associations but for real flexibility, the association process should be automatic). The set of capabilities that are needed include:[61]

- Discovery – applications must have ways to discover the sensors they need
- Advertisement – sensors must be able to advertise their presence on the network and to describe their capabilities and externally observable characteristics
- Binding and access control – sensors and applications must have means and protocols to agree on data stream subscription, including function, location, and security criteria
- Precedence resolution – for sensors that require control inputs to set parameters, a mechanism is needed to resolve which application has precedence when sensors can be shared; how precedence is established, when it expires, etc.
- Security – there must be means to manage data security across multiple overlapping groups and applications, as well as means to determine when sensors are lying or are malfunctioning

Legacy sensors and simple (non-smart) sensors and transducers can be used in an advanced sensor network by incorporating the concept of *micro-virtualization*. Distributed processing capability in the network provides local sensor abstraction for one or a few sensors attached at each of these points, with as many micro-virtualization platforms as needed in a given network. Processing capability for sensor micro-virtualization can be embedded in communication devices or can be attached to the network at or

[60] Consider a voltage control application that accesses a smart meter directly through the network vs. one that sends a request to a meter data head end, waits for the head end to query the meter, and waits until the head end provides a value back to the voltage application after the meter responds.
[61] Based on a discussion with Rick Geiger of Cisco Systems in the context of Internet of Things (IoT).

near the sensor site. Sensor micro-virtualization can also be included in coordinator nodes as described earlier in the section on Distributed Intelligence.

Sensor micro-virtualization can be employed in another manner as well. It enables the separation of smart sensors into two parts: a transducer with basic sampling, conversion, and communication capability, and a processing node that transforms raw samples into more abstract quantities, such as phasors. In this manner multiple transducers can share a single computing resource on a localized basis so that RTUs and PMUs are virtualized across multiple sensing points.

The sensor network physical and logical structures are illustrated in Figure 3.24 below. The left diagram shows a simplified physical structure in which a mix of smart and legacy sensors is integrated with a communication network and network services. Legacy sensors are micro-virtualized and applications are connected to the network at convenient locations, based on where computing resources are located. This may be in a substation, at a utility pole processor, in a grid control device, or in a communications device that supports application software.

The diagram on the right shows how the sensor network appears to various applications. Each application subscribes to data streams from the sensors it needs, thereby obtaining grid data at the lowest possible latency short of direct hard wiring. Micro-virtualization and network services are seamless, so that the applications do not have to be concerned with data acquisition details. In effect, the sensor virtualization platform concept has been moved to the communication network.

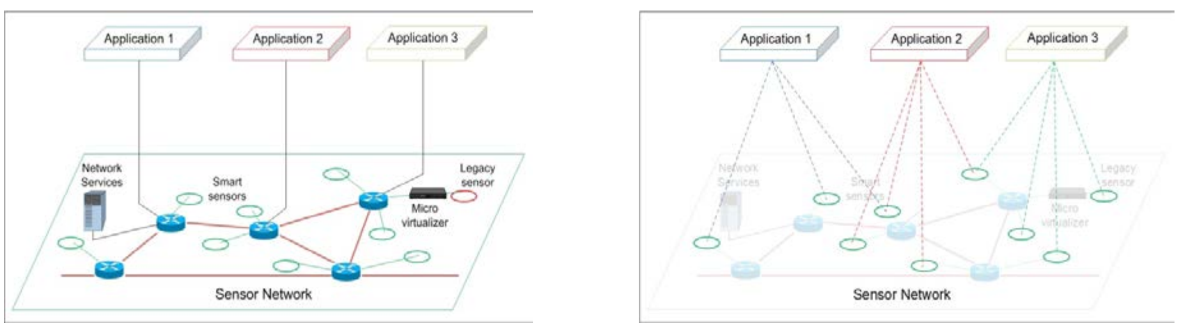

Figure 3.24. Physical and Logical Sensor Network Structure

The original application/virtualization platform/communication network/sensor set stack structure shown in Figure 3.23 has been re-partitioned into an application set and a services/communication net/sensor plane structure of Figure 3.24.

3.4.13 Synchronized Data Sampling

To support advanced grid applications involving fast dynamics, synchronized sampling is needed so that sample skew can be minimized or preferably eliminated. Three elements are needed to accomplish this:

1. High precision time distribution
2. Synchronized data sample acquisition
3. Time stamping

Note that time stamping alone is not sufficient. The samples must be *acquired* at as nearly the same time as possible, not just annotated with the time of acquisition. In order to accomplish this, each sampling device, whether it is a smart sensor or a data acquisition engine, must have the same sense of clock time to a high degree of precision. This can be accomplished via network time protocols but it must be noted that while modern communication networks distribute very precise timing internally, the interfaces to make this available to external applications is lacking (in particular NTP[62] does not provide granularity anywhere near what is available inside the networks themselves). Recent work at NIST[63] points out many of the issues to be addressed.

The distribution of timing in networks is somewhat complex but well understood (see Appendix D for more information on network timing distribution).

3.4.14 Multi-Level Aggregation and Distributed Intelligence Support

The communications network for a sensor system of this type must support both centralized and distributed analytics and control arrangements. In line with the distributed intelligence model described earlier, this means that the communication network for electric distribution systems must provide aggregation paths to the distribution substations as well as access to feeder level processing nodes.[64] In addition, if micro-virtualization or distributed data acquisition engines are to be used, localized data traffic that stays at the network level will consume some bandwidth and must be accounted for. Consequently, the underlying communication network must support general connectivity and peer-to-peer communication as opposed to the more common hub-and-spoke arrangement of standard distribution SCADA. In the context of laminar coordination structure, both per-to-peer and inter-layer hub-and-spoke data paths are needed.

3.4.15 Network Protocols and Services

The sensor network can use existing communication network protocols along with additional services supplied via attached processing to form a complete sensing and measurement platform. Among the key protocols and services are:

- Direct access to sensors via uniform open standard network protocols, including broadcast modes
- MPLS and PIM/SSM[65] for handling streaming data and providing a publish and subscribe mechanism for sensor data[66]
- Standard network management functions with extensions for sensor monitoring
- IEC CIM interface services – Generic Data Access, High Speed Data Access, Time Series Data Access, Generic Eventing and Subscription
- Sensor registry service and service advertisement

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[62] Network Time Protocol

[63] Marc Weiss, et.al., Time-Aware Applications, Computers, and Communications Systems, NIST Technical Note 1867, available online at http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1867.pdf

[64] S. Laval and B. Godwin, Duke Energy, Distributed Intelligence Platform (DIP) Reference Architecture, Vol. 1, available online at www.duke-energy.com/pdfs/dedistributedintelligenceplatformvol01.pdf

[65] Multi-Protocol Label Switching, Protocol Independent Multicast, and Source Specific Multicast

[66] P. Myrda, et. al., Recommended Approach to a NASPInet Architecture, 2012 45th Hawaii International Conference on System Sciences, January 2012, pp 2072-2081. Available online at https://www.computer.org/csdl/proceedings/hicss/2012/4525/00/4525c072.pdf

- IEEE 1451.4 TEDS (Transducer Electronics Data Sheets) service[67]
- Electrical network connectivity service
- Timing distribution
- Software Defined Networking interface services

The sensor registry service facilitates discovery of sensors. Alternately, service advertisement (by each sensor) can be used. The registry approach is easier to manage but is a centralized capability, whereas service advertisement is highly distributed and scalable but is not available from legacy sensors.

In order to separate the grid systems into a sensing network and other structures, sensors must be generally accessible. In conventional systems, sensors "belong" to a specific systems and that system manages the sensor meta-data such as calibration curves. The IEEE 1451 standard for smart sensors can be used to decouple sensors from applications. Smart sensors can incorporate the necessary information directly, but legacy sensors cannot. This is where the network service for TEDS comes into play: it provides the necessary sensor meta-data in a store accessible as a network service to any authorized application.

The electrical connectivity service is needed to provide context for sensor data and control actions. This implies continual re-discovery of electrical connectivity, since connectivity in most distribution systems changes on both short and long time scales. Hence this service has two parts: re-discovery, and application access support.

3.4.16 Network Level Cyber Security

Security for the sensor network must be an interlay in the network, as opposed to an overlay. The set of capabilities and services consists of four categories:

- Data integrity, confidentiality, and privacy – includes encryption (inter-nodal or end-to-end), key and certificate management, IPSEC, etc.
- Device and platform integrity – methods to ensure devices and systems have not been comprised at the hardware or code levels, including methods for ensuring supply chain integrity, tamper resistance/detection, signed firmware images, posture assessment, secure software life cycles, etc.
- Access control – identification, authentication, network access control, nodal access (sensor binding to applications), subscription control
- Intrusion detection and mitigation – signature and behavioral analysis, traffic analysis, node exclusion, non-repudiation, network segmentation, VLAN, etc.

3.4.17 Sensor Data Management

In order to support distributed control implementations, it is logical that data collection from distribution grids will be aggregated at the primary distribution substations, with some amount of that data being passed along to the control centers as well. Two methods of sensor and grid state data management are especially attractive in this environment and both make use of advanced communication network protocols:

[67] https://standards.ieee.org/develop/regauth/tut/1451d4.pdf

1. True distributed database – in this method, each data collection node maintains an in-memory database of its portion of the grid state; data is not duplicated across nodes; when an application queries a node for grid state data, if that data resides on another node, the distributed data base serializes the query, sends it to the node containing the data, receives the response and serves it up without the application needing to know the details of how the data was managed; this method relies upon peer-to-peer communication among the nodes to enable database operation, which can easily be supported in modern communication networks.
2. Network-based publish and subscribe – this method uses IP-Multicast, and specifically Source Specific Multicast to turn the communication network into a publish and subscribe mechanism in which any authorized process can subscribe to data from any publishing source; the communication network takes care of optimal packet replication in the case of multiple subscribers so that packet flooding does not occur; this method has been applied to managing PMU data flows on transmission level Wide Area Measurement System networks.[68] Each application can store data as needed.

Such methods were not practical in past Distribution Automation designs but availability of modern communication networks and grid devices makes these approaches feasible.

3.4.18 Observability Strategy

Sensing and measurement support multiple purposes in the modern grid environment and this applies equally as well to many other systems characterized by either geographic dispersal, or large numbers of ends points, especially when some form of control is required. Consequently, the sensing system design can be quite complex, involving issues such as physical parameter selection, sensor mix and placement optimization, measurement type and sample rate, data conversion, sensor calibration, and compensation for non-ideal sensor characteristics.

We may divide sensor networks into three classes:

- Type 1: those for which there is a physical presence but no particular underlying structure (such as battlefield surveillance networks)
- Type 2: those for which there is an underlying structured physical system (such as power grid sensor networks)
- Type 3: those for which there is no relevant physical system but there is a cyber-system, such as with social networks

Type 1 networks usually must provide general coverage of a target zone or area and so the topological concept of homology groups becomes a useful tool to determine coverage gaps,[69] which is a key issue with most applications involving Type 1 sensor networks. We will not discuss such networks any further here as they are not very useful in the utility setting. However, the concepts of homology groups and topology as tools for determining sufficient sensing for grid state determination are worth pursuing.

With Type 2 networks, we may take another approach based on the topological structure of the underlying physical system and the concept of system state. This means we do not need to resort to the concept of ad hoc randomly distributed meshes as is done for Type 1 sensor networks. Instead, for Type 2 networks, we employ the ideas of system state and observability, combined with an understanding of how

[68]Cisco, "PMU Networking with IP Multicast," available online at http://www.cisco.com/en/US/prod/collateral/routers/ps10967/ps10977/whitepaper_c11-697665.html.

[69]Vin De Silva and Robert Ghrist, Coverage in Sensor Networks via Persistent Homology, Algebraic and Geometric Topology, 7 (2007), pp 339 – 358. Available online at msp.org/agt/2007/07/agt-2007-07-016s.pdf .

the sensor data will be used to create an *observability strategy*. Such a strategy has several elements to it, as Figure 3.25 illustrates.

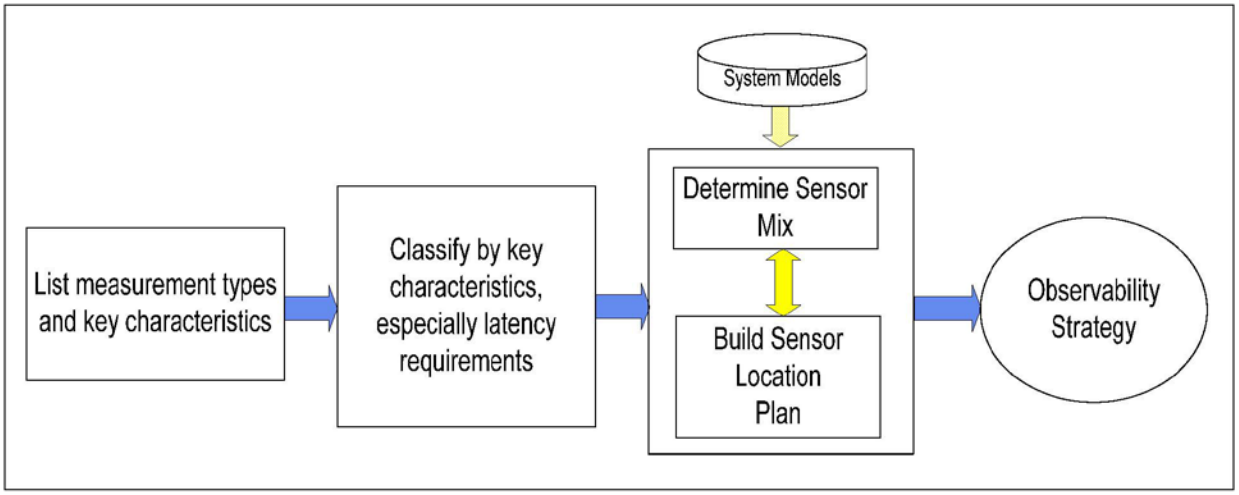

Figure 3.25. Type 2 Grid Observability Strategy Process Flow

The major elements of the strategy development process (simplified here) are:

- List measurement types and characteristics – a preliminary step to catalog all of the measurements needed to support grid observability; characteristics are needed for the next step
- Classify data by key characteristics – this step determines necessary constraints by allocating sensors to support various processes in the data latency hierarchy; in combination with grid structure
- Determine sensor mix and build sensor location plan – these two processes must often be done iteratively with each other; the issue here is a tradeoff between using large numbers of simple sensors and smaller numbers of more capable an expensive sensors; this is the essence of the optimization problem – by applying knowledge of the physical system being instrumented and computing the costs associated with the configuration at each iteration, one may arrive at a converged solution with reasonable assurance that the solution is good, if not absolutely optimal. If optimality is desired, tools such as mixed integer nonlinear programming may be employed.

Note that the process for Type 2 networks makes use of **system models**. In the case of power grids, this means the electrical topology of the grid, along with the inherent physical laws (Ohm's Law, Kirchhoff's Voltage Law, and Kirchhoff's Current Law) as well as the mathematical properties of planar graphs (Tellegen's Theorem, network duality, etc.). This means in practice that we do not need high density sensor meshes; instead, by applying knowledge of the physical nature of the grid, we can achieve significant economies by using limited numbers of well-placed sensors to obtain grid state. *This is a key issue to understand about grid state determination.*

The list of measurement types used in the development of the observability strategy comes from the set of applications and capabilities that must be supported. Ordinary grid control and asset management functions are well understood, but new measurement requirements are emerging due to the introduction of market mechanisms for DER at the distribution level. Such markets result in the design of both market products and market rules, with implications for grid management and control. These market products and rules have not typically been considered in the development of distribution grid instrumentation in the past.

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The introduction of market-control mechanisms (Transactive Energy) at the distribution level adds a new layer of complexity to distribution sensing and measurement architecture and design. Market products and rules must be included in the mix of sensing and measurement requirements, with corresponding impact on observability strategy, sensor allocation, and communication network design. This is especially crucial if real time distribution markets and concepts such as distribution locational marginal pricing are to be supported.

For social (Type 3) networks, the concept of state is not well defined, despite considerable recent research activity in the area. We can, however, outline a few items of interest. One is the formation of communities within a social networking system, sometimes referred to as clusters or cliques. This requires the discovery of logical connectivity, which parallels the power grid issue of electrical connectivity discovery and here we should make a distinction between social networking services, and the actual social networks that form on them. Various techniques are being explored to detect the existence of communities to measure their extents. The research on this is spread over a wide variety of disciplines[70, 71]. It is not clear that specific criteria exist for determining the state of a social network as of this writing.

Other activity has focused on understanding social network dynamics, as measured via economic activity like online bidding and other resource allocation and cooperation/competition interactions, using information theory and game theory as tools.[72] Another approach to social networks has been to mine them for information as if they constitute sensor networks themselves. An experimental effort in this direction is being carried out by the US Geologic Survey in attempting to use Twitter to detect and locate earthquakes.[73]

It is clear that social networks are part of the multi-network convergence involved in grid evolution, but more remains to be done to fully exploit this for measurement purposes.

3.4.19 Sensor Allocation

A key aspect of observability strategy and resultant sensor network design is the allocation of sensors: determination of appropriate sensors types and selecting the number and locations of the sensors. If sensors, sensor communications networks, and installation were all negligible cost, then one might just over-instrument a grid. However, this certainly not the case and even if the sensors were free, the cost to install them at arbitrarily high density would be prohibitive. This leads to a significant issue of sensor allocation optimization, which leads back to the use of the structural properties of Type 2 sensor networks.

[70] M.E.J. Newman and M. Girvan, Finding and Evaluating Community Structure in Networks, Physics Rev E, vol. 69, no. 2, 2004.

[71] M. Rosvall and C. T. Bergstrom, An Information-Theoretic Framework for Resolving Community Structure in Complex Networks, Proc. Nat. Acad. Sci. USA, vol. 104, No. 18, pp. 7327-731, 2007.

[72] Yan Chen and K. J. Ray Liu, Understanding Microeconomic Behaviors in Social Networking, IEEE Signal Processing Magazine, March 2012, pp. 53-64.

[73] See the USGS website page at http://recovery.doi.gov/press/us-geological-survey-twitter-earthquake-detector-ted/
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3.4.19.1 Transmission

Transmission grid state has traditionally been estimated from a system model and a sparse set of physical variable measurements. More recently, PMUs have been added to the transmission grids in North America and elsewhere for a variety of purposes but including improvement of grid observability. A number of studies have been carried out on optimal number and placement of PMUs on transmission systems. This has led to a rough design guideline that is suitable for observability strategy purposes: PMUs are needed on 1/3 of the buses in a transmission system to ensure complete observability.[74,75] It is still necessary to carry out the design and optimization process to determine the actual locations of these PMUs, but the guideline provides a key number. Engineers may decide that additional PMUs are needed or useful, so the guideline is just a starting point for the transmission observability strategy, and engineering knowledge of the system under consideration plus additional analysis may be need to handle unique cases.

3.4.19.2 Distribution

Observability for distribution grids is fundamentally a more difficult issue than for transmission for all but the simplest radial systems. Complicating factors include feeder branches and laterals, unbalanced circuits, poorly documented circuits, large numbers of attached loads and devices and, in the case of feeders with inter-ties, time-varying circuit topology. In general, circuit topology and device electrical connectivity may be poorly (incompletely or inaccurately or both) known. These issues make state estimation more difficult than for transmission systems, so it is necessary to rely more upon state measurement and less on estimation. In addition to perform sensing in support for grid protection and control and asset management, it is necessary in a modernized approach to also consider sensing and measurement in support of distribution level DER markets.

Sensors for distribution grids may be organized into three tiers. The top tier includes feeder sensing devices such as waveform recorders, digital relays, and PMUs located in the primary distribution substations. This tier also contains sensing for asset monitoring and power quality measurement.

The second tier includes devices located on feeders outside of the primary substations. At this tier there are five classes of devices:

1. Binary devices, such as Faulted Circuit Indicators (FCIs) – these devices indicate events such as the passage of a fault current at the sensing point
2. Line sensors – use analog transducers and digital processing to extract parameters from voltage and current waveforms, but measurements are not synchronized across the system
3. Distribution PMUs – distribution level phasor measurement units that extract current and voltage phasors that are synchronized across the system
4. Waveform recorders – these devices record waveforms with much denser sampling than other sensors, in order to capture high speed transient and high order harmonic information. Devices include power quality monitors and transient event recorders. They may record continually or may be triggered by grid events to retain a window of waveform data leading up to, including, and trailing the event.

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[74]Baldwin, T.L., Mili, L., Boisen, M. B., Jr., Adapa, R., "Power System Observability with Minimal Phasor Measurement Placement", IEEE Transactions on Power Systems, 1993, p. 707-715.

[75]Mudassir A. Maniar, et. al., Optimal Location of Phasor Measurement Unit for Complete Network Observability of Power System, Global Research Analysis, International, March 2013. Available online.: http://worldwidejournals.com/gra//file.php?val=March_2013_1363598665_05d91_27.pdf

5. Grid device controllers – many grid devices such as capacitor banks have controllers that have electrical sensing capabilities; they may be useful as sensing devices when they can be networked to the communication system

The third tier includes devices connected to the feeder secondary, such as meters and frequency disturbance monitors. It is important to understand the performance characteristics of each sensor type, especially the rate at which data can be extracted from them. This allows one to match sensor types against latency requirements for the various data classes to be handled by the sensor system.

From an architectural standpoint, the use of meters as a sensor fabric presents some issues. Generally, the only way to access voltages from meters is to interface at the meter data collection engine (DCE), normally located in the control center, but in some cases may actually be in the enterprise data center. If the meter data is being used for control in a centralized control environment, having the meter DCE in the control center is acceptable; having it in the enterprise data center is problematic. If control is distributed to the primary substations, then use of the meter data in any low latency control application is somewhat problematic unless the meters are individually addressable without the need to go through the meter DCE.

In the case where communication to devices on the Low Voltage grid is via Power Line Communication (PLC), a special problem exists in that the communication physical layer can be disrupted by a fault that we wish to detect, characterize, locate, and isolate using that selfsame physical layer for communication with the sensors and control devices.

3.4.20 Sensor Allocation Optimization

The design of a sensing network for a modern power grid should be viewed and formulated as an optimization problem. Fundamentally, we wish to minimize Capital Expenditure (CapEx) while managing (bounding) Operational Expenditure (OpEx) over a time horizon and yet ensure that observability requirements are met. This can be formulated mathematically; the solution requires the use of sophisticated mathematical and software tools, such optimizations have been performed to determine best locations for reclosers to maximize reliability, and best locations for PMUs on transmission systems, among other goals.

The objective functions can take either of two forms:

- Maximize the observability for a given budget
- Minimize the cost to achieve a given amount of observability

Sensor type, number, and location are the solution variables. The problem may be complicated by the presence and need to use legacy sensors that already have given locations and capabilities. Sensor allocation optimization is a design level problem, to be applied to the feeders for a given distribution grid, but sensor system architecture provides a structure within which to perform the optimization.

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>
> Distribution has historically been the least instrumented aspect of the grid but has the greatest need for observability as DER penetration proceeds. Tools to aid planning and design for distribution grid sensor networks that take into account grid structure, market-control requirements, and legacy components and constraints are not available but are greatly needed.

3.5 Selected Communication Network Architecture Issues

PMU deployment in the U.S. is widespread and continuing, with most of the focus on grid state and system instability analytics. Closed loop protection and control applications have been considered but remain undeveloped. This section provides some wide area communications networking considerations for two transmission level PMU-based applications: wide area backup protection and inter-area oscillation damping.

3.5.1 Architectural View: Wide Area Closed Loop Backup Protection

The proliferation of PMUs creates an opportunity to address many of the shortcomings of present approaches to backup protection, including:

- Costliness of maintaining protection coordination of distance elements
- Loss of coordination expertise due to retirements
- Susceptibility to mis-operation problems
- Vulnerability to errors caused by bad physical data

The use of PMUs for closed loop backup protection can offer dramatic advantages by resolving these shortcomings. The PMU–based approach is inherently self-monitoring, won't trip on swings, and provides precise control of out-of-step protection trips and islanding strategy, is faster than step distance backup, and does not require coordination studies.[76] However, the crucial nature of protection functions places special focus on communications networks given that wide area protection most likely will involve third party communication service provider networks, rather than ones built and operated privately by the utilities. Figure 3.26 shows the basic structure for a communications network to connect transmission substations relays and PMUs to backup protection at a transmission operations center.

Note that this configuration is essentially a dual redundant network arrangement of the type that is used for internet access for data centers. Networking inside the substations is not detailed but has been fully developed already in the private sector using multiple network topologies and protocols such as HSRP and PRP.[77] The structure of Figure 3.26[78] could be made stronger by making dual hub-and-spoke connections from each relay set (blue and red) to both networks.

[76] E. Udren, Quanta Technology, LLC, Principles for Practical Wide-Area Backup Protection with Synchrophasor Communications, paper B5-112-2014, CIGRE 2014, available online at: http://digilib.monenco.com/documents/10157/2529643/B5_112_2014.pdf
[77] Hot Standby Router Protocol and Parallel Redundancy Protocol.
[78] Diagram based on work by E. Udren and D. Novosel of Quanta Technology, LLC.

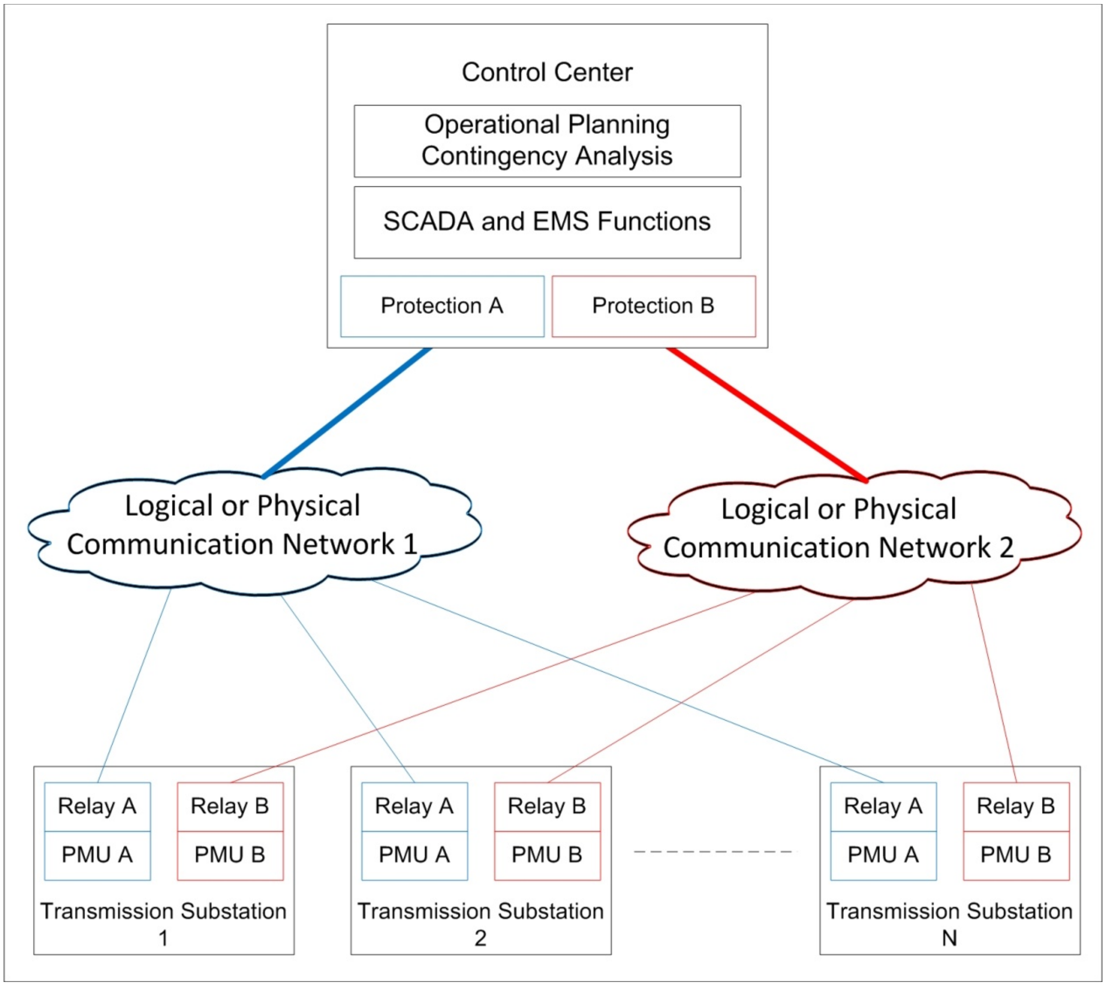

Figure 3.26. Backup Protection Networking

Following the standard practice of data centers, an implication of Figure 3.26 is that the protection system would use two different physical networks from two different communication service providers to improve resiliency.

3.5.2 Architectural View: Inter-Area Oscillation Damping and Software Defined Networking

Software Defined Networking (SDN) is defined by the Open Networking Foundation as "the separation of the communication network control and data plane that decouples the network control and forwarding functions enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services."[79] In the present context, the applications of interest are wide area protection and control functions, particularly wide area closed loop controls. An example is the use of transmission level power electronics in the form of a Universal Power Flow Controller (UPFC) device, combined with a pair of phasor measurement units, to automatically dampen inter-area oscillations.[80] Often in power systems control work, the communication network has been assumed to be more or less ideal but in practice actual network latency can be quite detrimental to

[79] https://www.opennetworking.org/sdn-resources/sdn-definition

[80] For a use case description from EPRI, see http://smartgrid.epri.com/UseCases/Inter-AreaOscillationDamping.pdf

closed loop control. Figure 3.27 shows a schematic version of such a control with two PMUs providing the sensor feedback signals to the inter-area oscillation damping controller. The controller sends signals to the Universal Power Flow Controller (UPFC) device, which is the final control element that adjusts grid parameters to dampen the oscillations and stabilize the system.

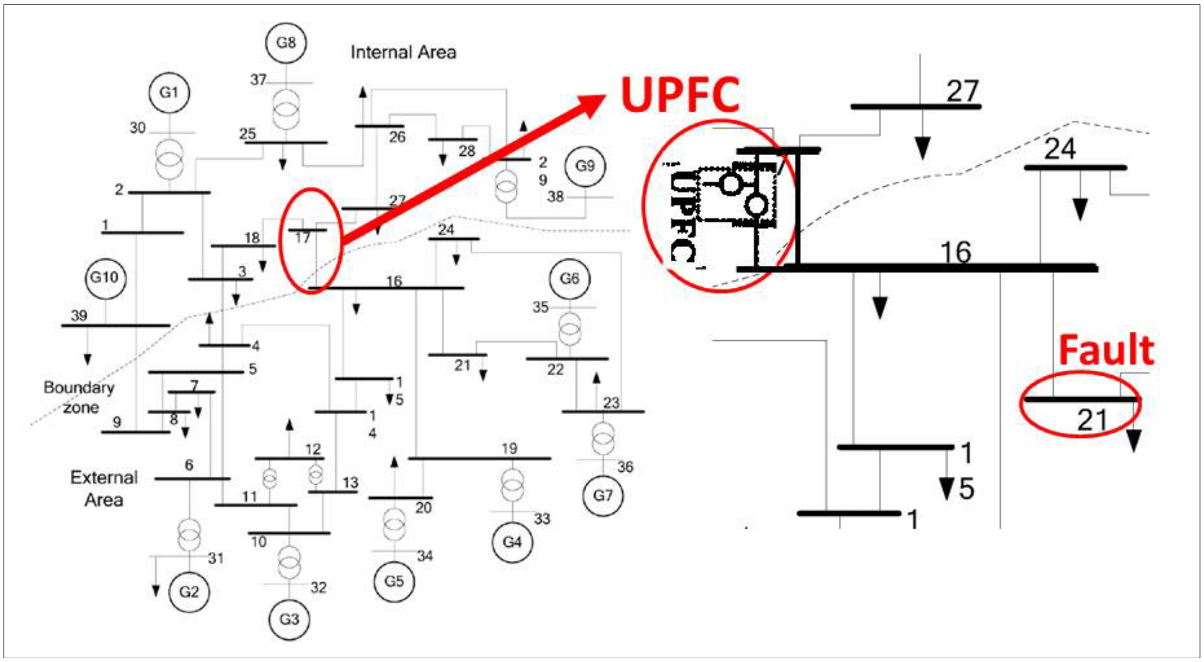

Figure 3.27. Wide Area Damping Physical Arrangement

Figure 3.28[81] shows a graph of the damping behavior of a UPFC system with three differing amounts of latency in receiving the remote PMU signal. As can be seen, latency can cause the damping control to destabilize so that the oscillation does not dampen out.

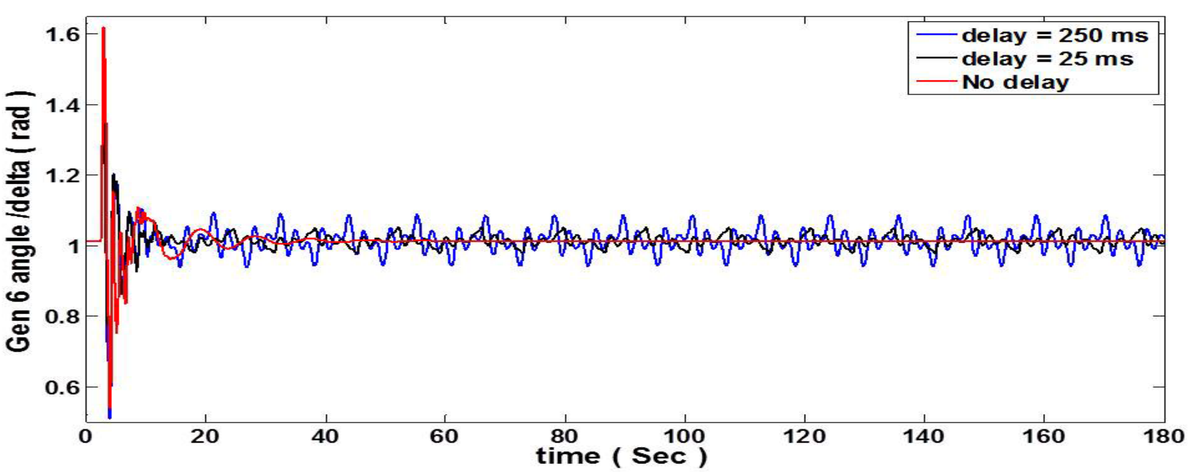

Figure 3.28. Effect of Communication Latency on Damping Control

[81] From a simulation of the 10-Generator 39-Bus system with a UPFC connecting buses 16 and 17 for oscillation damping, with various measurement communication delays. Simulation work performed by Renke Huang at PNNL.

Figure 3.29 shows the system in schematic form. From this representation it is easier to see the essential structure: a damping control feedback loop is closed around the system for stabilization, and a second loop provides interaction between the damping controller and the network by way of the SDN interface. Both measurement and control signals may pass through the communication network (depicted here as a cloud) although in some arrangements the controller is co-located with the final control element so no wide area networking is needed for the control signal. The communication portions of the latencies illustrated in Figure 3.19 in the Sensing and Measurement Architecture section above occur in this cloud.

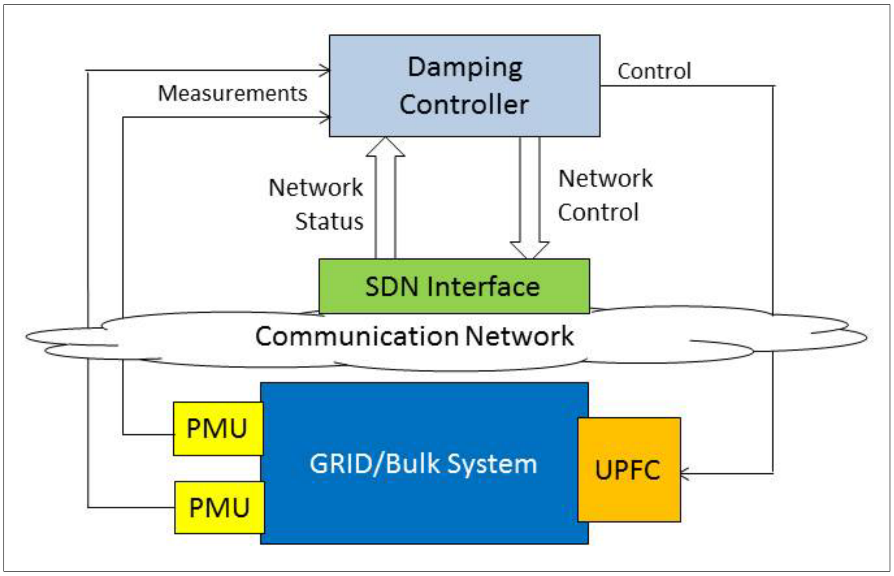

Figure 3.29. Wide Area Control with SDN Schematic

The controller-SDN loop is not intended to operate as a standard closed loop control. Its purpose is to enable two-way collaboration between the damping controller and the network to manage performance of the damping loop. The interaction modes are:

- The controller uses data on network conditions and performance to adjust its own compensator parameters and sample rates to be stable under existing network conditions such as path latencies, thus adapting to overall system dynamics
- The controller adjusts network paths and other parameters to fit the requirements of the control algorithm, this tuning the network to controller specifications

Presently, SDN is being used to optimize network performance for data centers and to automate service orchestration for network provisioning. However, it has potential to further aid the convergence of communication and control for wider area utility networks by providing the network interface to a converged control/coordination/communication platform.

Communication network performance is not fixed and the network elements can and do introduce latencies, jitter, and skew that can affect loop stability and Protection and Control (PAC) performance. Large networks can introduce variable delays (which are time-varying as the network changes routing), and skew when different paths exist for multiple sensors sending data to the same controller or when the controller is sending commands to multiple final control elements. Simply specifying that the network be deterministic is unrealistic for wide area control; while there is work on using deterministic Ethernet for control networks, that method does not work across multiple network administrative domains. PMU networks attempt to alleviate this by roughly scheduling samples and by time stamping the actual sample messages (usually using GPS-derived timing); this is fine for non-real time analytics but is problematic for closed loop control. The concepts of latency margin and jitter margin are at least conceptually useful[82] but both are difficult to apply to real power grids.

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As grid dynamics and sensor data rates continue to increase, network design for grid protection and control becomes increasingly crucial. It is not sufficient just for controls and communication networks to be **considered together** when planning/designing a modernized grid, it is also necessary for controls and communications to be capable of **working together operationally** in an interactive and dynamic manner.

Two big needs in this area are tools to provide joint control/communication design, and wide area networks with SDN interfaces that can be accessed by control systems. The latter is especially an issue for service-provider networks because the service provider may want to maintain sole access to the SDN interfaces to prevent multiple controllers from clashing. Hence, a mechanism for grid control access to SDN on wide area networks will become a needed network service.

[82] A. Cervin, et. al., The Jitter Margin and Its Application in the Design of Real-Time Control Systems, available online at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.416.3641&rep=rep1&type=pdf

4.0 Summary

Grid Architecture makes use of advanced system architecture principles, combined with network theory, control theory, and software engineering to provide grid modernization stakeholders of all kinds with advanced insights in support of the decisions they must make. The methodology makes use of emerging utility industry trends and advanced paradigms to provide insights that are largely focused on grid structure. This report describes seven paradigm shifts that have proven especially useful for Grid Architecture work. Chief among these is the focus on structure and representation of the grid as a network of structures.

Multi-layer mapping is presented as a means to put architectures on an analytics footing for purposes of validation, comparison, and optimization. Doing so entails careful definition and separation of grid properties and qualities, and the use of mathematical concepts to provide sufficient rigor for analytical methods to apply. This results in a set of grid qualities that can be orthogonalized and used in tools that allow grid stakeholders to adapt and optimize reference grid architectures to their specific needs.

New representations for grid control show how the bulk energy system is already transactive in nature in those regions where organized central markets exist at the ISO/RTO level. This puts distribution level transactive energy into the larger grid context and clarifies the roles of proposed Distribution System Operators and ISOs/RTOs in a full transactive environment. They also show why planning processes and capacity markets are part of the grid management and control schema and must be thought of as integral with markets and controls when developing new tools for grid modernization.

Laminar Coordination is explained in more detail than in the original Grid Architecture report, and the concept of the coordination node as an abstract component is outlined. The coordination nodes and associated domains and intra-domain message buses support a wide variety of potential distributed intelligence and control designs, including those for networks of microgrids.

Market and controls and their essential limits are discussed, with the insight that bounds do in fact exist in terms of temporal and endpoint (horizontal locational) density.

Sensing and measurement for architecture power grids is defined using the concept of extended grid state. A new architecture view is presented that re-partitions sensing, communications, and applications differently from tradition grid system designs. The purpose of the sensor network architecture is to provide improved scalability and flexibility in grid sensing while supporting low latency applications requirements for fast distribution dynamics.

Finally, two architectural views focused on wide area protection and control show how communication networks must be considered jointly with the development of the protection and control applications, and how making the communications network work interactively with the control application have the potential to improve the performance of both.

The report provides 17 Architectural Insights that support advanced grid modernization.

Appendix A

Emerging Trends
(2015 Update)

Appendix A

Emerging Trends

Table A.1 contains the complete updated trends list, including the original trend set from the first Grid Architecture report prepared for the Department of Energy in 2014.

Table A.1. Updated Emerging Utility Trends for 2015

Trend	Description	Comments
Increasing data volumes from the grid; variety of data is also increasing due to diversity of device types and increasing observability	While much of the discussion around increasing volumes of data from the grid focused on meter data, in fact 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 Phasor Measurement Units (PMUs) that will be installed on the US transmission grid will produce vast volumes of data (about 1.5 Petabyte/year). The vast amounts of data from PMUs is due to that fact that 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 Transmission.	In addition, as interest in asset monitoring continues to increase, vast new volumes of asset health and operational data will be generated, some to be used in real time, 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.
Faster system dynamics	The implementation of new grid capabilities has brought with it 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 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	Old style distribution control was on times 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. 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 PMU data rates are now typically 30-60 readings per second-too much for human operators to comprehend at the raw data level.

	acquisition and transport, analysis, and automated decision and control.	
Hidden feedbacks and cross-coupling	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.	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 case 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.
RPS and other regulations and VER penetration	The trend of converting from traditional thermal generation to renewables such as solar and wind (known as Variable Energy Resources or VER) is supported by public policy at the Federal level and also at the state level (through Renewables Portfolio Standards or RPS). Since wind and solar PV do not provide the rotational inertia of the traditional generation they displace, system inertia is gradually decreasing. In CA, 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.	Since VER is not dispatchable the way traditional generation is, new control problems arise for a system originally designed around the concepts of power balance and load-following generation control. The inertia reduction issue has not yet reached serious proportions in bulk power grids, but this problem, in on the radar screens of several utilities such as SCE. Solutions to these problems may involve new types of grid components and controls, and re-purposing of older device types with new controls.
Changing fuel mix	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 have to 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.
Evolving industry/business models and structure	It has become obvious that the penetration of new functions at the distribution level, along with responsive loads and distributed generation is causing the original mode of distribution operations to become inadequate. Proceedings in Hawaii, New York, and California are all aimed at reconsidering the roles and responsibilities of	The DSO 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

	distribution grid operators as is much thought leadership in the industry at large.	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 DSO's vs. independent DSO's is also unresolved.
Evolving control system structure	Utility controls 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.
Increasing need for advanced planning processes, methods, and tools	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.
Midstream generation	Connection of small (20 MW) gas-fired generators to natural gas at midstream, 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.	Implications for T&D planning; coordination with gas infrastructure; this decreases congestion in both electric transmission and gas transmission.
The 85% microgrid	Evolving designs for microgrids get 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.
Storage	Significant goals 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	Multiple use cases identified; may also be useful for augmenting system inertia via advanced control. Fast, bilateral storage combined with

	advances and market forces.	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 (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.
Increasing complexity of grid control problems and application of optimization methods to solve them	Large scale grid control problems are becoming increasingly complex as we add new functions/requirements. In many cases, we wish to do optimization as a matter of the goals we seek (optimize load profiles, or minimize carbon emissions, for example). In many 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: DR/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 DR, for example.	Integrated Volt/VAr control is already formulated as an optimization problem with minimization of 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/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.
Building to grid convergence	Commercial building owners and grid operators are recognizing the potential value of going beyond traditional demand response to allow for	The issues of building to grid integration involve not only interface specifications but at a higher level,

	two way exchange of energy services.	logical function specifications so that the control systems on both sides have something to say once they are able to talk to each other.
Increasing focus on grid resilience	Issues are well known.	Issues are well known.
Increasing focus on grid physical and cyber security	Issues are well known.	Issues are well known.
Coordination between Balancing Authorities	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.
Load aggregation and DG aggregation companies as power market participants	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; Note: however, DG aggregators such as solar leasing companies often target jurisdictions/geographies where existing utility rate structure gives them a competitive economic advantage.
Missing money and resource adequacy	Increasing penetration of renewable energy sources, such as, wind and solar with low or zero marginal production costs cause 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.	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.
Retirement of coal and nuclear plants	The recent EPA rules regarding greenhouse gas emissions from coal plants are stipulated to lead to early retirement of over 75GW 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.
Development and deployment of "smart" inverters	Controllable power electronics used in DC/AC inverters that connect some forms of 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.	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.
DG at scale implies less volume on the transmission systems	As the generation model bifurcation continues, and as midstream generation via gas increases, there will be reduced need for electric transmission services.	Seems to have implications for transmission business models, as well as planning.
New desired capabilities raise new issues for data privacy and confidentiality	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	Most schemes for secondary control of large numbers of endpoints assume sharing of some kinds of data that are not shared today.

	concerns still apply.	
Consumer choice	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 DS, and through organization via microgrids, local energy networks, and via formation of Consumer Choice Aggregators (CCA's). 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 (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/prosumers self-organize.
Responsive loads	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.	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.
Load composition is changing.	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.	Implications for controllability and responsiveness, as well as impacts on business models, and energy value streams.

Information and communication technologies continue their convergence with the power grid.	Decreasing cost of both computing and networking, plus the synergy of combined computing and networking, plus the prevalence of embedded computing in a wide variety of grid and edge devices impacts all levels of the grid, its users, and utilities.	Convergence implies common architecture for synergy, and development of new value streams, both of which are emerging for the utility worlds. Examples include the gradual move toward using communication and edge devices as application platforms.
Penetration of generation at Distribution level (both dispatchable and stochastic) - partial inversion of the generation model	Generation has traditionally been centralized and connected at Transmission. Increasingly, distributed generation is being connected at the Distribution level. Sources may be traditional spinning generation (diesel, nat. gas, propane, and biomass) or may be non-traditional renewables, especially solar PV, and thus a mix of dispatchable and stochastic forms is evolving on distribution grids. Most of this generation is 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 (net metering, feed-in tariffs, etc.) much of this generation can connect to the grid and impact grid operations. Even when not grid-connected, DG 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 DG 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, control coordination is less well developed. Causes a split in regulatory jurisdictions 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 to those and bulk system organized markets coordinate?
Penetration of stochastic generation sources impacts grid control and economics; diversity of load is expanding to diversity of generation.	Traditional generation has been dispatchable (this includes fixed generation which is dispatchable by turning it on and off); 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.	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/AGC, which is the basis for large scale grid control. Oversupply of power from wind or solar can cause not just balance 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 max (e.g. 45 mph), which negatively impacts grid control stability.
Loss of system rotational inertia due to replacement of traditional generation with wind and solar PV.	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. Replacement of heavy rotating machines with high rotational inertia with these sources causes an overall system level decrease in inertia.	System and individual generator inertias play a role in transient stability (via Rate of Change of Frequency or 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.
Aging infrastructure/aging workforce/legacy systems	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 so as to maintain a Business as Usual 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 may not occur for decades in most cases, even though the current crop of AMI solutions is weak.
Obsolete value-of-service models	Some grid investment decisions, especially those related to "hardening" and grid resilience are based on models of the value of electric service dating to	Investment in measures that would improve grid resilience are hampered by undervalued grid service. By

	the 1980's.	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.
Storage is being added to the grid, driven by policy and need	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.	In addition to the obvious uses such as leveling out the variations of stochastic sources, storage can be used to supply certain ancillary services (up and down frequency regulation for example) and could be used for entirely new services such as virtual synchronous generation for replacement of lost rotational inertia.
Protection methods are becoming inadequate	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 or system conditions is largely a theoretical concept.	Protective relaying covering components, zones, areas (RAS) and systems (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.
DG/DS/DR are hiding real demand and introducing apparent load volatility	The effect of both DG and DR is to make the demand on the grid less, but when DG and DR 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. DS 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 distort 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/DR. 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 DSO's.
Resource adequacy in regions with restructured power 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.	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.

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Appendix B

General Grid Control Models

Appendix B

General Grid Control Models

Figure B.1 depicts the general grid control model with no DSO. Note that planning and the associated capacity auction markets are considered part of the overall grid control process.

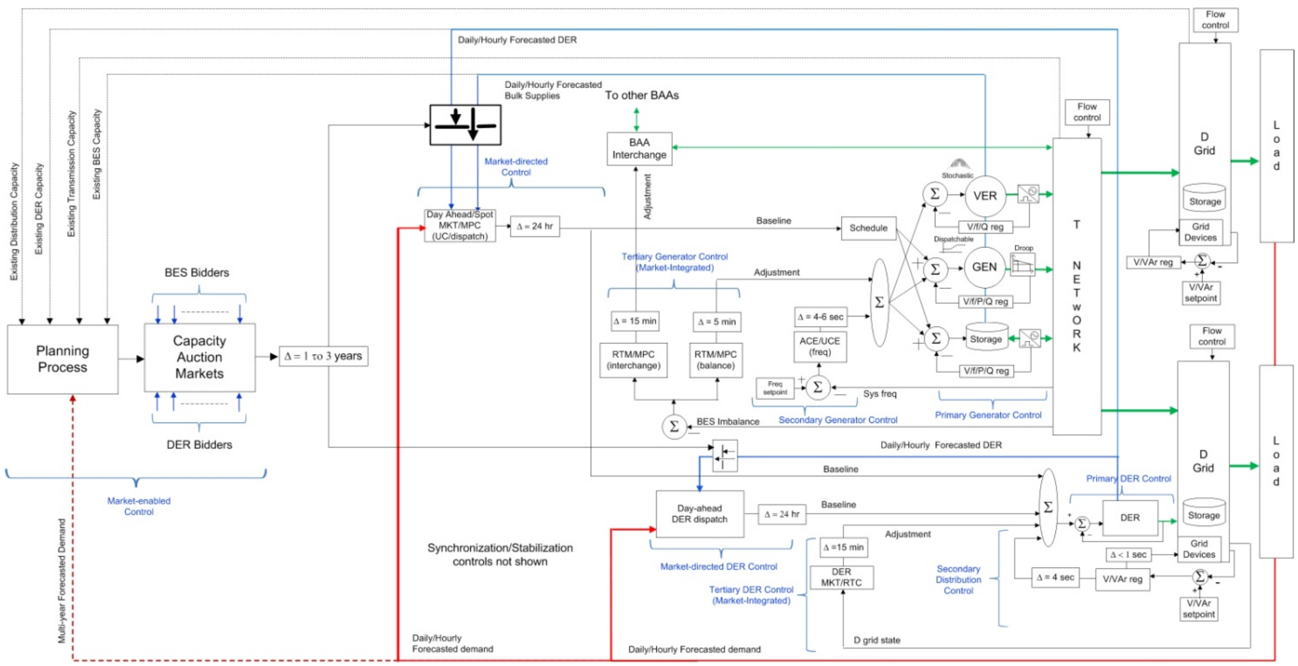

Figure B.1. General Grid Control Model, No DSO

Figure B.2 below depicts the general grid control model with DSO management of DER.

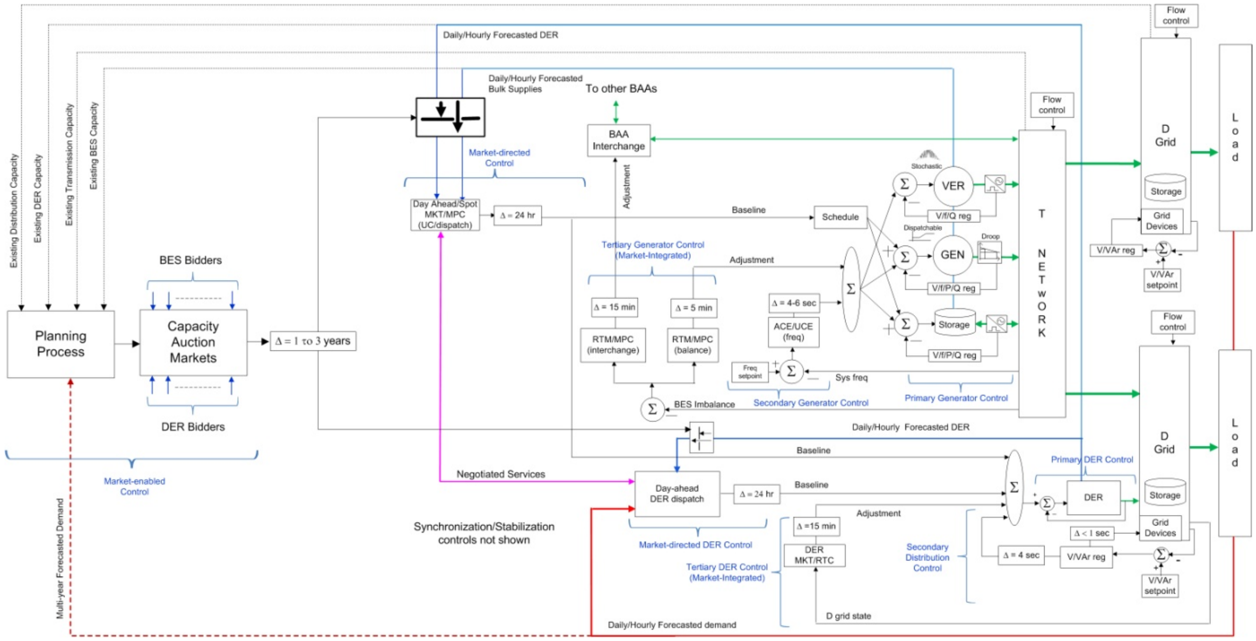

Figure B.2. General Grid Control Model with DSO

Appendix C

Grid Architecture Web Page Screen Shots

Appendix C

Grid Architecture Web Page Screen Shots

The figures below contain screenshots from the Grid Architecture website as of December, 2015.

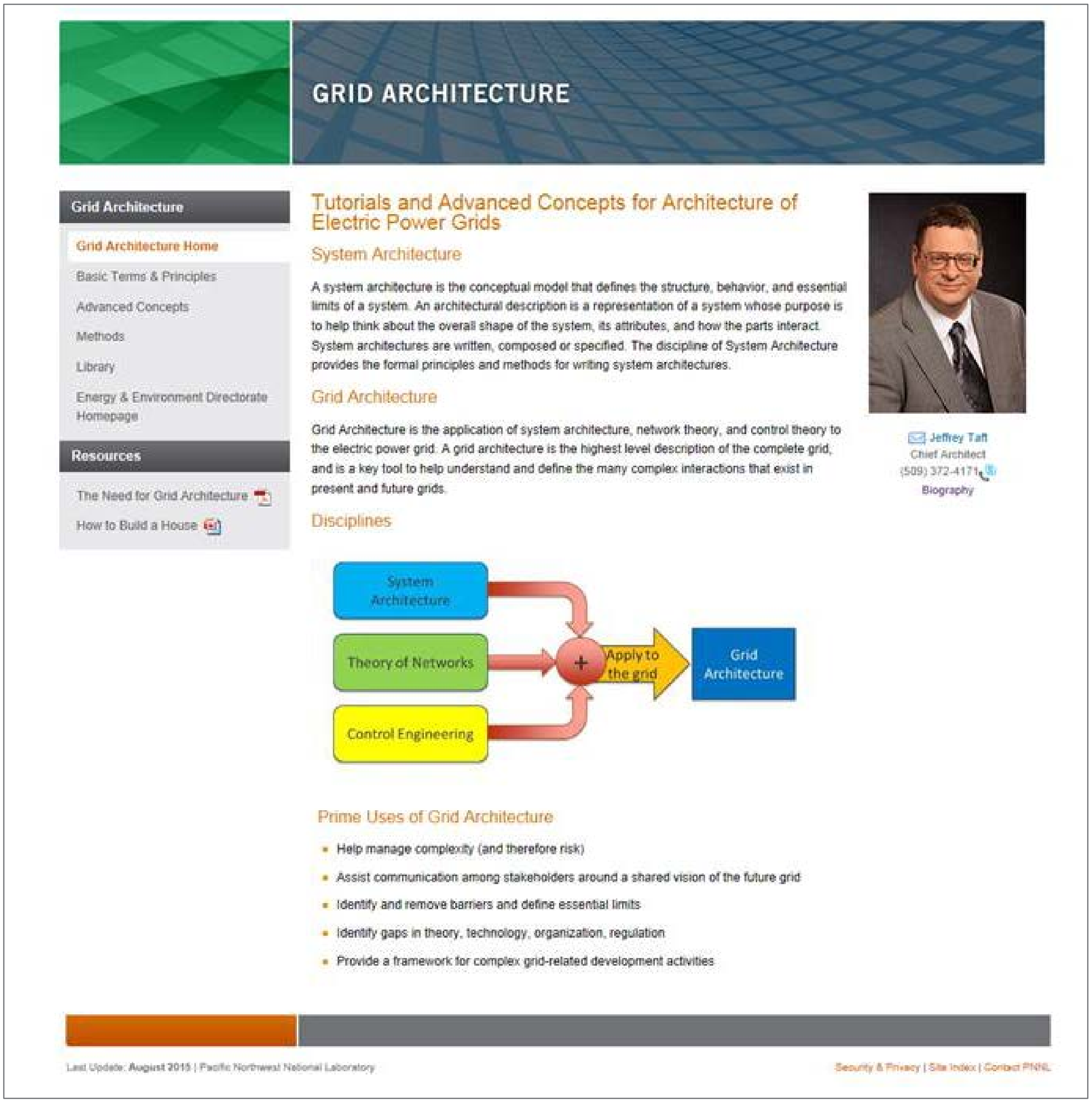

Figure C.1. Grid Architecture Website Page 1

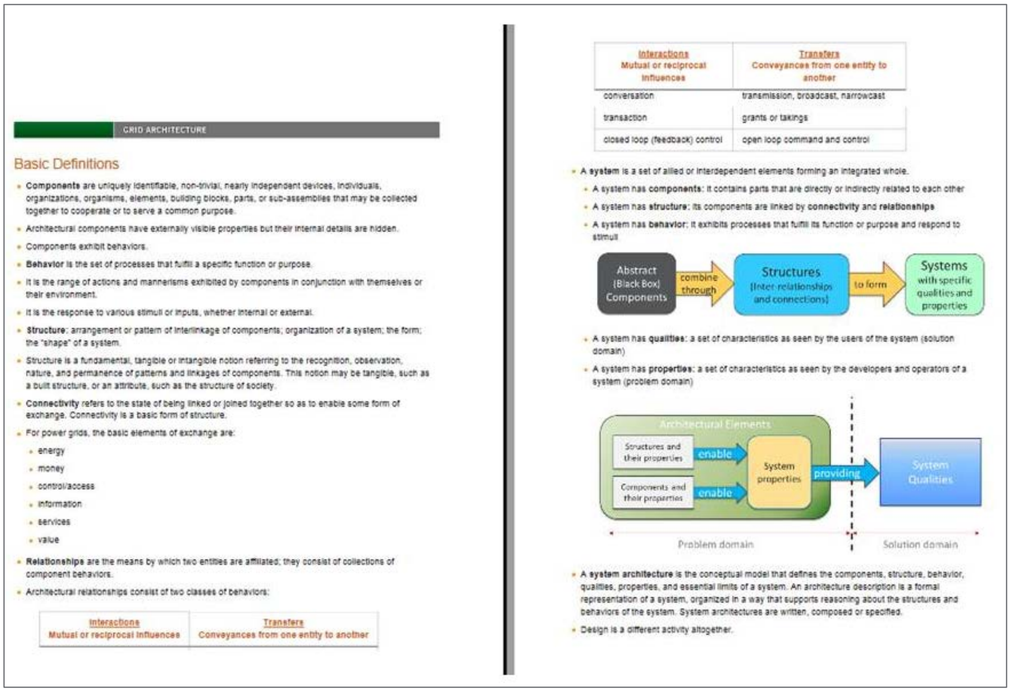

Figure C.2. Grid Architecture Website Page 2 (partial)

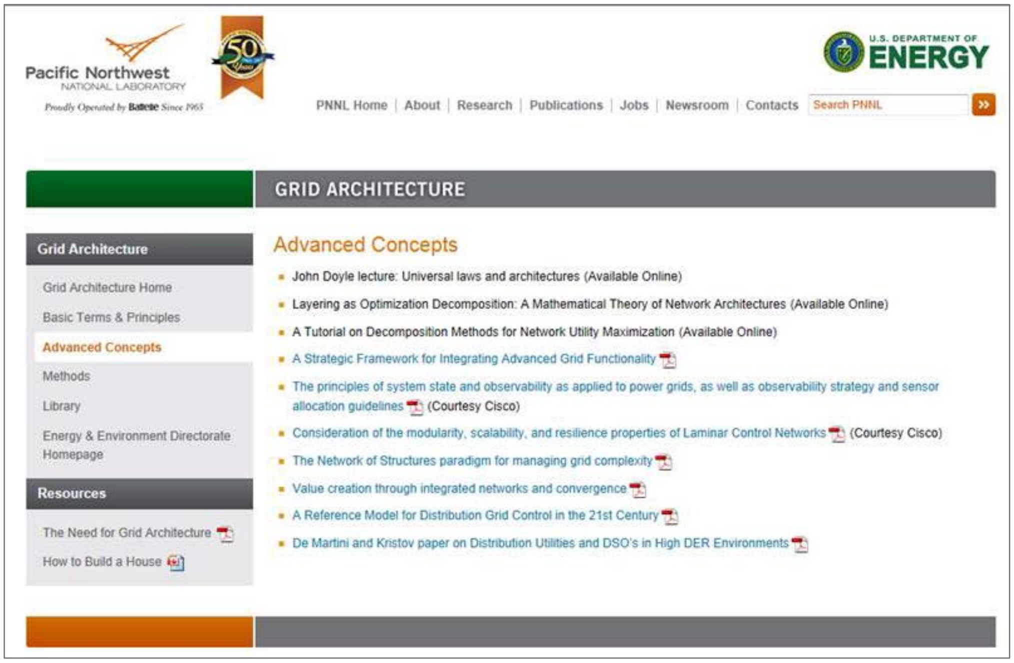

Figure C.3. Grid Architecture Website Page 3

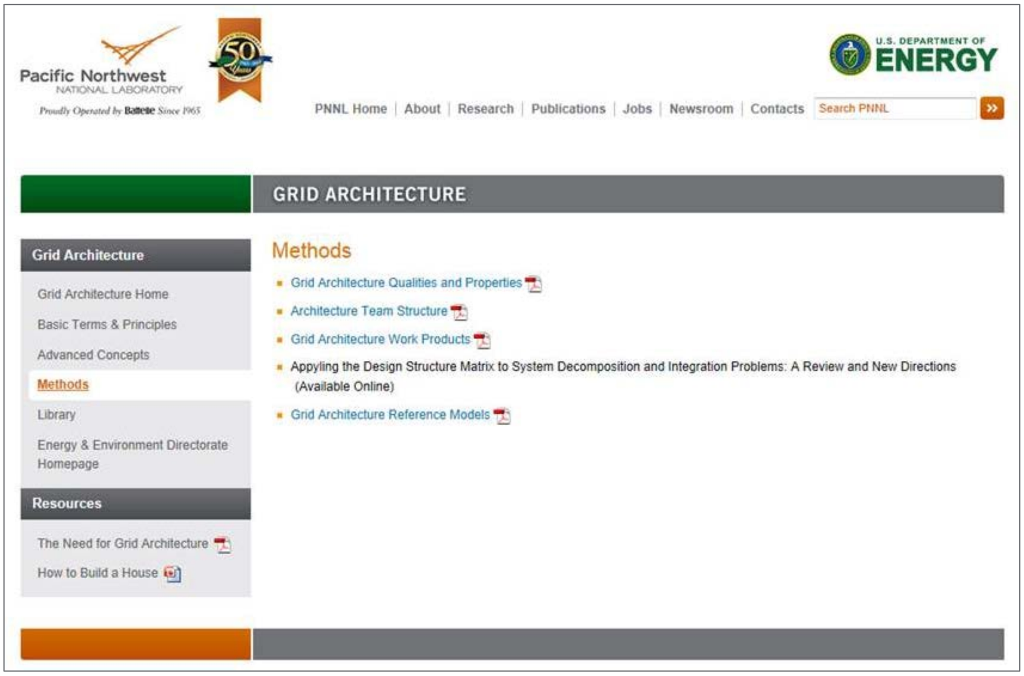

Figure C.4. Grid Architecture Website Page 4

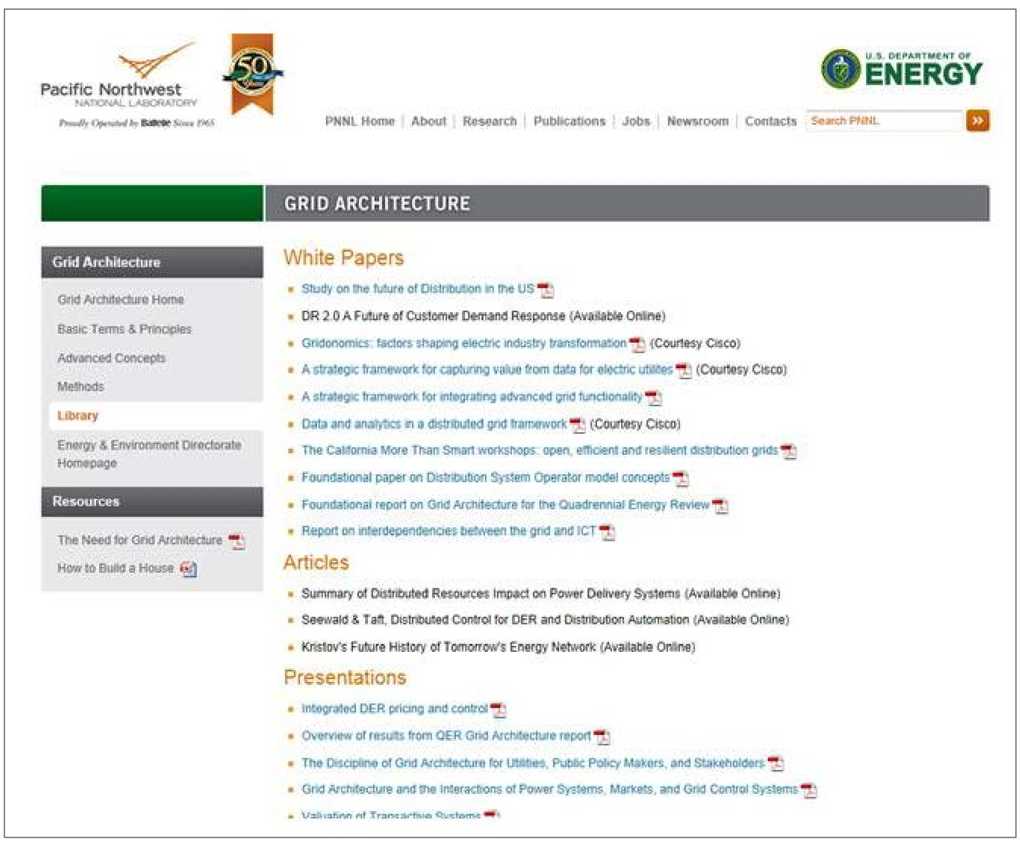

Figure C.5. Grid Architecture Website Page 5

Appendix D

Network Timing Distribution

Appendix D

Network Timing Distribution

In the utility industry, it has been common to put GPS satellite receivers in substation to provide local time synchronized across wide areas. Recently utilities have begun to look for ways to reduce reliance on GPS and to see network-based methods for time distribution and synchronization.

Network-based timing distribution within a single system or organization is straightforward. However, in the electric grid context, multiple systems, organizations and network domains are usually involved. In such cases, timing distribution is complex but well developed, involving as it does multiple types of network clocks and considerable network structure. Figure D.1 below illustrates the structure for two organizations. In the diagram, GNSS refers to Global Navigation Satellite System and PTP refers to the Precision Time Protocol (IEEE 1588). A profile specifically for power systems have been developed (IEEE C37.238-2011, known as the 1588 Power Profile) to support sub-microsecond precision and accuracy which is needed for acceptable synchrophasor performance.[83]

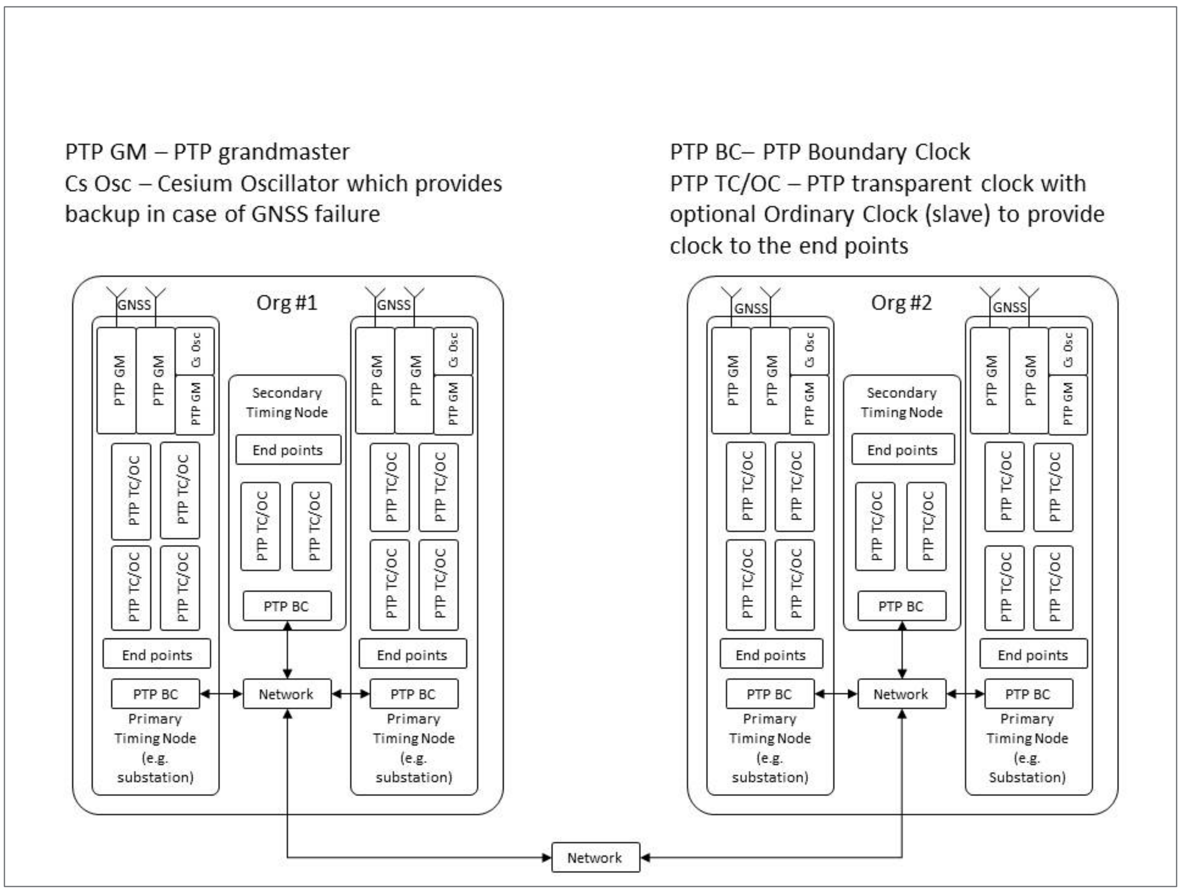

Figure D.1. Multi-Domain Network Time Distribution – diagram © Cisco, used with permission

[83] D. Arnold, IEEE 1588 Study Group, Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications, March 2013, available online at http://www.microsemi.com/document-portal/doc_view/133475-profile-for-use-of-ieee-1588-precision-time-protocol-in-power-system-applications

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