



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Grid Architecture

Final

January 2015

JD Taft
A Becker-Dippmann



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

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

**Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov**

**Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: <http://www.ntis.gov/ordering.htm>**



This document was printed on recycled paper.

(9/2003)

Grid Architecture

Release 3.0

January 2015

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

Pacific Northwest National Laboratory
Richland, Washington 99352

Contents

1.0	Background and Purposes	1.1
2.0	Scope and Focus of This Work.....	2.1
3.0	Brief Introduction to Grid Architecture.....	3.1
3.1	How Grid Architecture Can Be Used.....	3.3
3.2	Why Grid Architecture Should Be Used.....	3.3
4.0	Starting Point: Selected Architectural Representations of the Existing Grid	4.1
4.1	Macro Structure.....	4.1
4.2	Industry Structures	4.5
4.2.1	Vertically Integrated Utilities.....	4.6
4.2.2	ISO/RTO-based Utilities	4.8
4.2.3	Public Power/Municipal Utilities/Electric Cooperatives.....	4.9
4.3	Markets, Services, and Business/Value Stream Frameworks	4.12
4.3.1	Value Stream Structure for Vertically Integrated Markets.....	4.13
4.3.2	Value Stream Structure for Hybrid Markets	4.14
4.3.3	Value Stream Structure for Texas	4.15
4.3.4	Value Stream Structure for Independent Aggregator Markets.....	4.16
4.3.5	Value Attachment.....	4.17
4.4	Electric Structure.....	4.20
4.4.1	Transmission/Bulk Power System Structure.....	4.23
4.4.2	Primary Substations.....	4.23
4.4.3	Distribution Circuits.....	4.24
4.5	Basic Electric Coupling Model	4.28
4.6	Dynamic Interaction Model	4.30
4.7	Control/Coordination Framework	4.33
5.0	Selected Architectural Views for the Grid of 2030	5.1
5.1	Desired Qualities List.....	5.1
5.2	Key System Properties Supporting These Qualities.....	5.3
5.3	Key Future Grid Components and Structures	5.3
5.3.1	Mappings.....	5.5
5.3.2	Selected Architectural Elements	5.8
5.3.2.1	Buildings	5.8
5.3.2.2	Microgrids	5.10
5.3.2.3	Storage.....	5.11
5.3.2.4	Whole Grid Coordination.....	5.14
5.3.2.5	Industry (DSO) Model and Distribution System Operators	5.18
5.3.2.6	Flexible Distribution Circuits	5.24

6.0	Case Studies.....	6.1
6.1	Storage as System Inertia Augmentation in a Multi-Services Environment	6.1
6.2	Electricity/Natural Gas Interaction.....	6.2
6.3	Advanced Flexible Distribution	6.5
7.0	Conclusions	7.1
7.1	Industry Structure	7.1
7.2	Business/Value Streams	7.1
7.3	Electric & Power System Structure.....	7.2
7.4	Control/Coordination Framework	7.3
7.5	Grid Architecture 2030.....	7.3
	Appendix A - Architectural Principles.....	A.1
	Appendix B - Glossary	B.1
	Appendix C - Basic Quantitative Assessment of Architectures: Map Analytics	C.1
	Appendix D - Definitions of DOE Desired Grid Qualities	D.1
	Appendix E - Fundamental Basis for Laminar Coordination	E.1
	Appendix F - Works Reviewed for This Project.....	F.1
	Appendix G - Emerging Utility Industry Trends	G.1

Figures

3.1	Relationship of Architecture to Qualities	3.1
3.2	Architecture Development Process Inputs and Outputs	3.2
3.3	Architecture Process Flow	3.3
4.1	US Interconnections.....	4.1
4.2	Reliability Regions and Balancing Authorities.....	4.2
4.3	Texas Distribution Utility Service Areas	4.3
4.4	Geographic Encapsulation	4.4
4.5	Vertically Integrated Structure Model	4.7
4.6	ISO/RTO-Based Industry Model	4.9
4.7	Public Power/Municipal/PUD/Cooperative Structure Model.....	4.10
4.8.	Vertical Integration Value Stream Structure.....	4.13
4.9	Hybrid Markets Value Stream Structure.....	4.14
4.10	Texas Value Stream Structure	4.15
4.11	Energy Services/Aggregator Value Stream Structure.....	4.16
4.12	Value Attachment in ISO/RTO-Based Markets.....	4.18
4.13	Basic Electric Structure	4.21
4.14	Transmission Circuit Meshing	4.23

4.15 Substation Bus Structures	4.24
4.16 Typical Radial Feeder Structure	4.25
4.17 Common Distribution Looping Arrangements	4.26
4.18 Dense Urban Distribution Circuit Mesh	4.27
4.19 Basic Direct Electric Coupling	4.29
4.20 Grid Coupling Structure.....	4.31
4.21 Whole Grid Control Model.....	4.35
4.22 Bulk System Control/Market Integration.....	4.36
4.23 Grid Coordination Structure	4.37
5.1 Mappings for the Partial Architecture.....	5.6
5.2 Tracing the Impact of Laminar Coordination on Qualities.....	5.7
5.3 Tracing Storage Impact on Robustness.....	5.8
5.4 Coordination Node and Domain	5.16
5.5 Essential Coordination Structure	5.17
5.6 Mapping Laminar Coordination to Grid and Buildings.....	5.18
5.7 DSO Industry Structure	5.20
5.8 Uncluttered DSO Model	5.21
5.9 Clarified DSO Structure.....	5.22
5.10 DSO-Based Coordination Structure.....	5.23
5.11 DSO Value Stream Structure	5.24
5.12 Flexible Distribution Grid Structure Illustration.....	5.26
6.1 Combined Grid Damping and Virtual Inertia from Storage	6.1
6.2 Electric and Gas Infrastructure Overlay	6.3
6.3 Loop Isolation in Gas/Electric Networks.....	6.3
6.4 Effect of Midstream Generation	6.4
6.5 Flexible Distribution Circuit.....	6.5

Tables

4.1 Power System Services Definitions and Properties	4.19
5.1 Key Grid Components	5.4
5.2 Key Grid Structures	5.5
5.3 Key Building Characteristics	5.9
5.4 Key Microgrid Characteristics.....	5.10
5.5 Storage Application Characteristics.....	5.11
5.6 Flexible Mesh Elements.....	5.25

1.0 Background and Purposes

This work was done at the request of the U.S. Department of Energy (DOE), specifically with respect to issues relevant to U.S. electric transmission, storage and distribution infrastructure. This work has several purposes:

- To provide organized views and insights about the existing U.S. grid as a means of identifying structural constraints to grid modernization;
- To provide selected potential future views of portions of grid architecture that address important emerging trends and systemic issues;
- To help identify issues that may have public policy implications;
- To explain and illustrate the principles of system architecture, and apply those principles to model potential futures of the electricity system. Such an exercise links the components, structures and properties of the system to specific system qualities that operationalize desired outcomes or objectives of public policy.

In the course of this work, two comment sessions were held with representatives of the utility industry, as well as DOE. The inputs provided in those sessions were very helpful in shaping the content of this work, as were the many discussions with DOE officials and staff, members of national laboratories, and the key persons from the utility industry, both during and outside the comment sessions.

Why Read this Document?

This document, while only representing a beginning of the task of creating a full U.S. electric grid reference architecture, provides a number of key insights into existing limitations of the 20th Century grid vs the needs of the 21st Century grid, many of which are not recognized as the essential structural limitations that they actually are. It also provides selected views into a possible future where the grid (especially at the distribution level) becomes a platform for energy innovation, with coordination (not centralized command and control) of many types of resources, allowing multiple control and market mechanisms and approaches to coexist on and connected to the grid simultaneously without compromising electric reliability. Finally, it illustrates how the formal discipline of system architecture in the specialized form of grid architecture makes it possible to devise rigorous architectures, to understand the impact of various architectural choices on resulting system qualities, and to evaluate architectural options and competing architectures quantitatively.

Throughout the paper architectural insights and policy implications are identified in colored text boxes; key questions are identified and answered in text boxes as well, all in order to highlight takeaways.

It is not the contention of this document that there is exactly and only one “best” architecture but rather that the use of these methods makes it possible to find good architectures for the grid, to understand cost-constrained tradeoffs, and to shape the essential guidelines and “rules of engagement” by which the grid should evolve in the 21st Century.

2.0 Scope and Focus of This Work

Full grid architecture has many aspects, some of which exceed the scope of this limited work. Instead, guidance from DOE led to the consideration of a subset of grid architecture issues, based on their centrality to understanding key structural considerations and their linkage to critical emerging trends. As a result, this paper describes a “partial” architecture, which focuses on the following areas:

- Electric structure/grid topology;
- Industry structure;
- Coordination framework;
- Business/Value streams;
- Electric/gas interactions;
- Buildings, microgrids, storage, power flow control/conversion, distributed generation; and
- Potential impacts on regulation and markets.

Since this document describes a **partial architecture**, some topics that are clearly related will not be covered in any depth. This does not mean they lack importance; it simply means that those topics did not fall within the requested scope of this work or could not be treated in detail due to time limitations. However, where necessary, those areas were given consideration in the process of creating the structure models provided in this paper.

Section 3 contains a brief discussion on basic aspects of system architecture as it is applied to power grids. It focuses on the relationships of grid components and structures to the resultant properties of the grid and how they support the desired system qualities determined by end user needs and public policy.

Section 4 provides a set of architectural views for the U.S. grid **as it exists today**. These views are used to point out various structural limitations that must be addressed for the grid of the 21st Century. Specific issues illustrate these limitations, but it is not the purpose of this section to resolve those issues individually.

Section 5 then introduces a partial architectural model using desired grid qualities provided by DOE. Selected forward-looking architectural view involving three specific structures and three advanced components are used to illustrate how grid architecture organizes system complexity and how new structures can address limitations in the grid.

Section 6 contains three case studies: one for use of fast storage to augment system inertia, one to illustrate the interconnection and convergence of two related networks, namely the electric and gas networks, and one to illustrate the emerging concept of flexible distribution grids.

Section 7 contains a summary and conclusions.

Several appendices are located at the end of the paper, including a Glossary. **Appendix F** contains a table of prior and current works in the area of power grid architecture – these were reviewed and considered in the process of creating this document and some comments on their impact is included.

3.0 Brief Introduction to Grid Architecture

In this section, the concept of formal system architecture is introduced as a general methodology and tool set, and then the specialization of this to electric power grids, grid architecture, is introduced.

System architecture is a discipline for describing, analyzing, and communicating structural representations of complex systems. Colloquially, a system architecture is a model of a (complex) system, the purpose of which is to help think about the overall shape of the system, its attributes, and how the parts interact. In the development of complex systems, the creation of architecture precedes system design.

Some uses of system architecture include:

- Managing complexity and therefore risk;
- Identifying gaps in theory or technology;
- Communication among stakeholders (internal and external);
- Untangling emergent ambiguity in organizational roles and responsibilities related to new functions;
- Enabling prediction of system qualities;
- Reducing or eliminating structural barriers to functionality and value stream formation;
- Determining convergences, and analyzing changes to system structure.

System architectures consist of descriptions of abstract components, structures, and externally visible properties of a real or proposed system. These are combined to provide a system with a defined set of system qualities (aspirational requirements or goals). The relationships among these elements are shown in Figure 3.1 below.

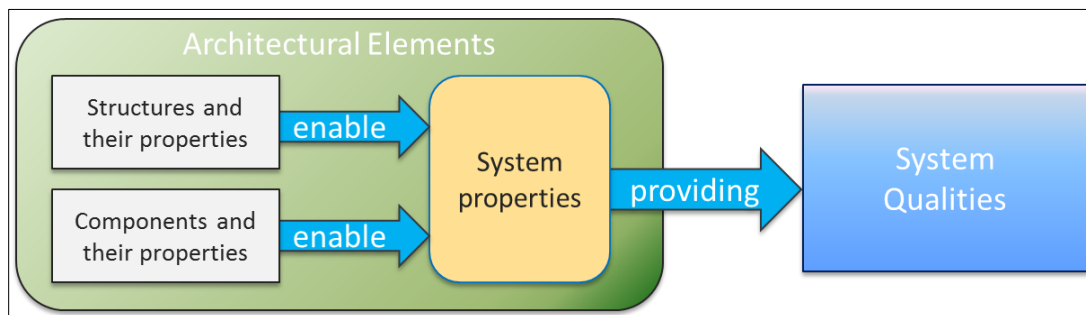


Figure 3.1. Relationship of Architecture to Qualities

Architecture development starts with the end in mind—that is, with the desired system qualities—and works backward to define the system properties and then the components and structures, along with their properties. An overview of the process inputs and outputs is illustrated in Figure 3.2 below.

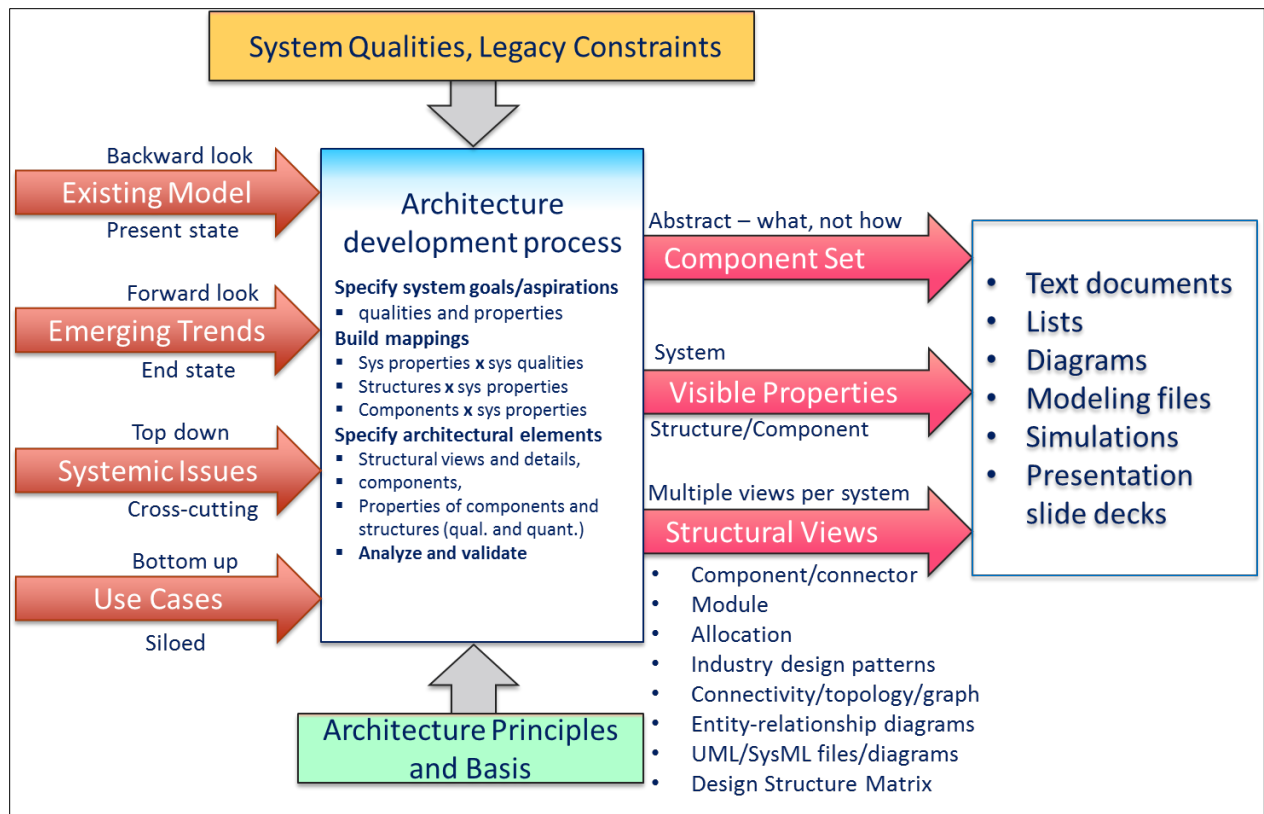


Figure 3.2. Architecture Development Process Inputs and Outputs

Grid architecture is the specialization of system architecture for electric power grids. As such, it includes not just information systems, but also industry, regulatory, and market structure; electric system structure and grid control framework; communications networks; data management structure; and many elements that exist outside the utility but that interact with the grid, such as buildings, merchant distributed energy resources (DER), and microgrids.

System architecture in general and grid architecture specifically make use of a set of architectural principles, or rules, to guide architecture development and aid in evaluation. Where possible, system architecture also makes use of rigorous bases for architectural structure, thus minimizing the “artistic” aspects of the architecture. For grid architecture, the rigor issue is crucial, because managing and changing the grid necessarily cuts across multiple disciplines such as control engineering, market operations, and industry structure. See Appendix 1 for a list of general system architecture principles and a second list of some more specific grid architecture principles.

Grid architecture starts (as any architecture does) with the needs of the end users of the grid. These are shaped by public policy and that combination leads to a set of desired grid qualities. The architecture development process flows from this point. Figure 3.3 illustrates the process. The detailed process involves mechanisms for stakeholder input and validation along the way not illustrated here.

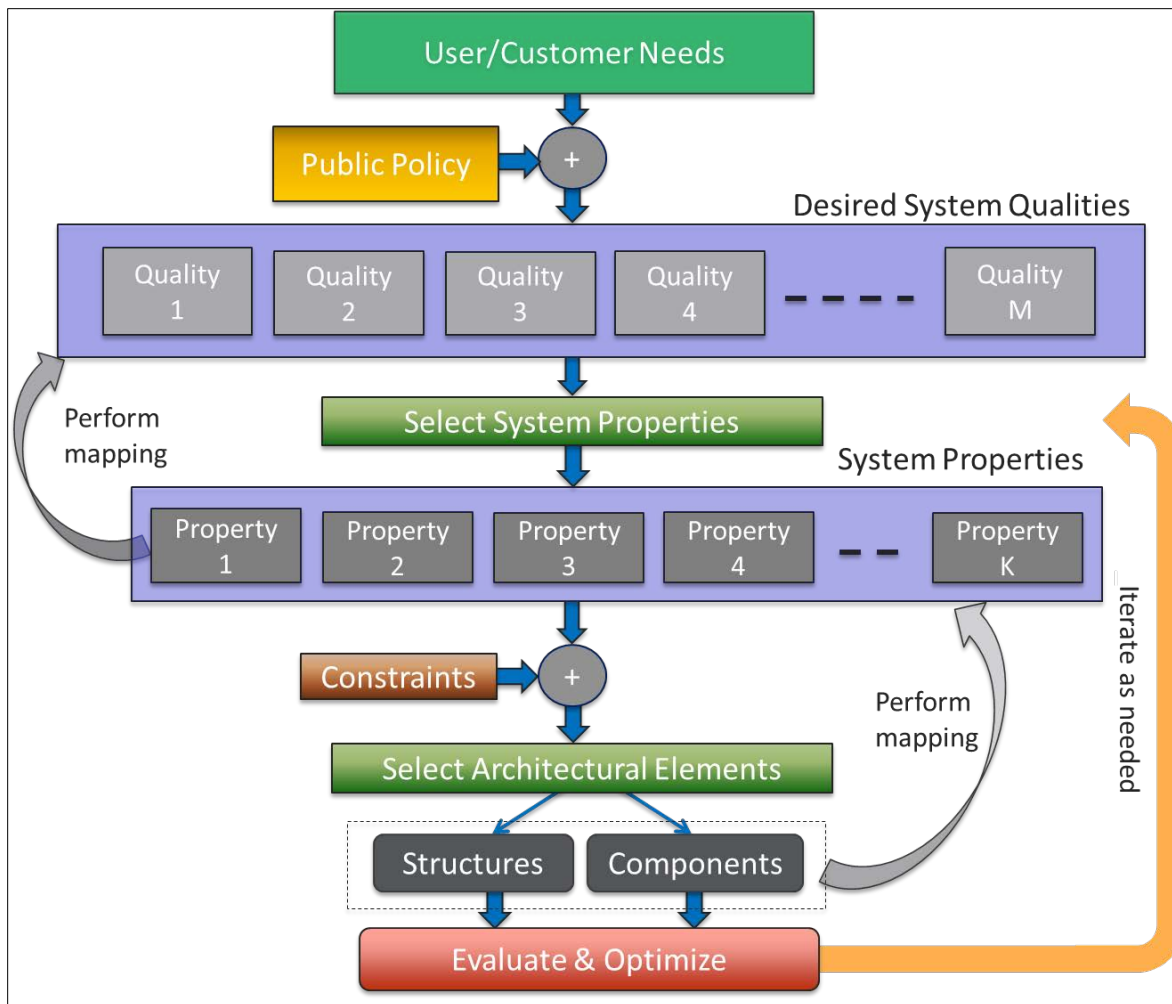


Figure 3.3. Architecture Process Flow

3.1 How Grid Architecture Can Be Used

The fact that grid architecture operates with certain abstractions does not mean that it is an academic exercise. It is in fact a very practical tool for obtaining insights at the system level across multiple relevant domains (grid, markets, control, industry roles, etc.). The industry has recognized that the complexity of the power grid has passed the point where intuitive or siloed approaches to changes are workable.¹ Architecture provides the disciplines and methods to view the grid from a **system standpoint**, and to share those views with stakeholders. It organizes information in ways that provide significant insights not available through other means.

3.2 Why Grid Architecture Should Be Used

The power of grid architecture is ultimately in its ability to aid in managing complexity.

¹ Proceedings of the *Future of the Grid –Evolving to Meet America’s Needs National Summit* (June 26, 2014; DOE-OE/GridWise Alliance); https://www.smartgrid.gov/sites/default/files/Preread_materials_National_Summit.pdf

The dangers of *not* using grid architecture are:

- Increasing risk of creating unintended consequences detrimental to resilient operations, such as those emerging at the interaction of certain grid functions previously considered in isolation;²
- Increasing risk of massive stranded investments in infrastructure, such as have already happened;³
- Blockage of energy innovation and resultant value streams associated with new products and services; and
- The mismatch of policy directives and operational realities associated with the grid, which have emerged in the context of certain early market approaches.⁴

Use of grid architecture is the difference between being able to actively shape the grid of the future based on sound representation of a multiplicity of structures and the interactions involved, versus passively allowing the grid to evolve in a bottom-up manner and waiting to see what emerges.

Architectural Insight 1

Grid architecture provides the discipline to manage the complexity and the risk associated with changing the grid in a manner that significantly reduces the likelihood of unintended consequences.

Key Question 1

Where Does the Discipline of System Architecture Come From?

System architecture has arisen from the development of complex systems in several fields, and key work on the methods has been done at institutions such as California Institute of Technology, Carnegie Mellon University Software Engineering Institute, MIT, Princeton, and elsewhere. Some of its methods trace back as far as the 1960's but much of the work is more recent, having emerged in response to the exponentially increasing complexity of intelligent systems.

Grid architecture is a specialization of system architecture that includes additional elements from control engineering, communications/networking, data management, organizational structure, energy/power markets, and utility regulatory structure.

² Medina, et al, "Demand Response and Distribution Grid Operations: Opportunities and Challenges", IEEE Trans. On Smart Grid, September, 2010, pp 193-198

³ Michael Puttre, "Is Your Solar Inverter Smart Enough for California's Grid?" Solar Industry, Aug, 2013, available online: http://www.solarindustrymag.com/e107_plugins/content/content.php?content.13089

⁴ Lorenzo Kristof, "Prepared Direct Testimony of Lorenzo Kristof," FERC, Docket ER06-____-000, 2006.

4.0 Starting Point: Selected Architectural Representations of the Existing Grid

4.1 Macro Structure

The US electric power system is widely understood to be complex, but is rarely represented in its entirety with appropriate regional and industry segment variations; nor is the control structure of what is commonly referred to as “the grid” available in a single depiction. Certain aspects are widely depicted, however, as illustrated in the two figures below. The US power grid is divided geographically at many levels, the top three of which are interconnections, reliability regions, and balancing authority areas. Each interconnection is a single synchronous machine, and the three interconnections in the contiguous states are controlled separately, although power exchanges between interconnections are provided via inter-tie stations.⁵

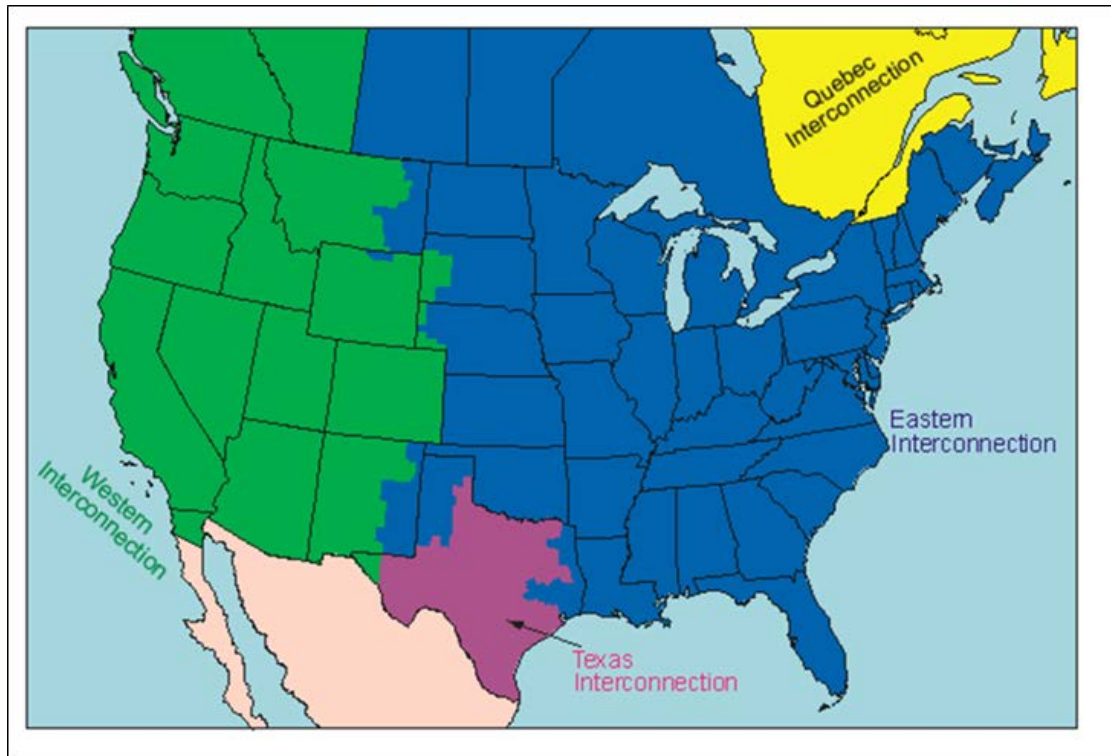


Figure 4.1. US Interconnections

Within interconnections, grids are divided into reliability regions, with reliability coordinators overseeing each. Reliability coordinators have an event-driven kind of control function, in which they continuously monitor grid state within their regions, and perform various operational and contingency analyses, issuing alerts and directives when certain reliability issues occur or are forecasted to occur.

Within the reliability regions, grids are further broken into Balancing Authority Areas, each with a Balancing Authority (BA) that performs certain control functions, including generation dispatch and

⁵ Note that there is also a smaller interconnection in Alaska, and a major Canadian interconnection in the northeastern part of North America.

balance, interchange scheduling with neighboring balancing authority areas, and load frequency control. Various changes to BA structure have been investigated.⁶

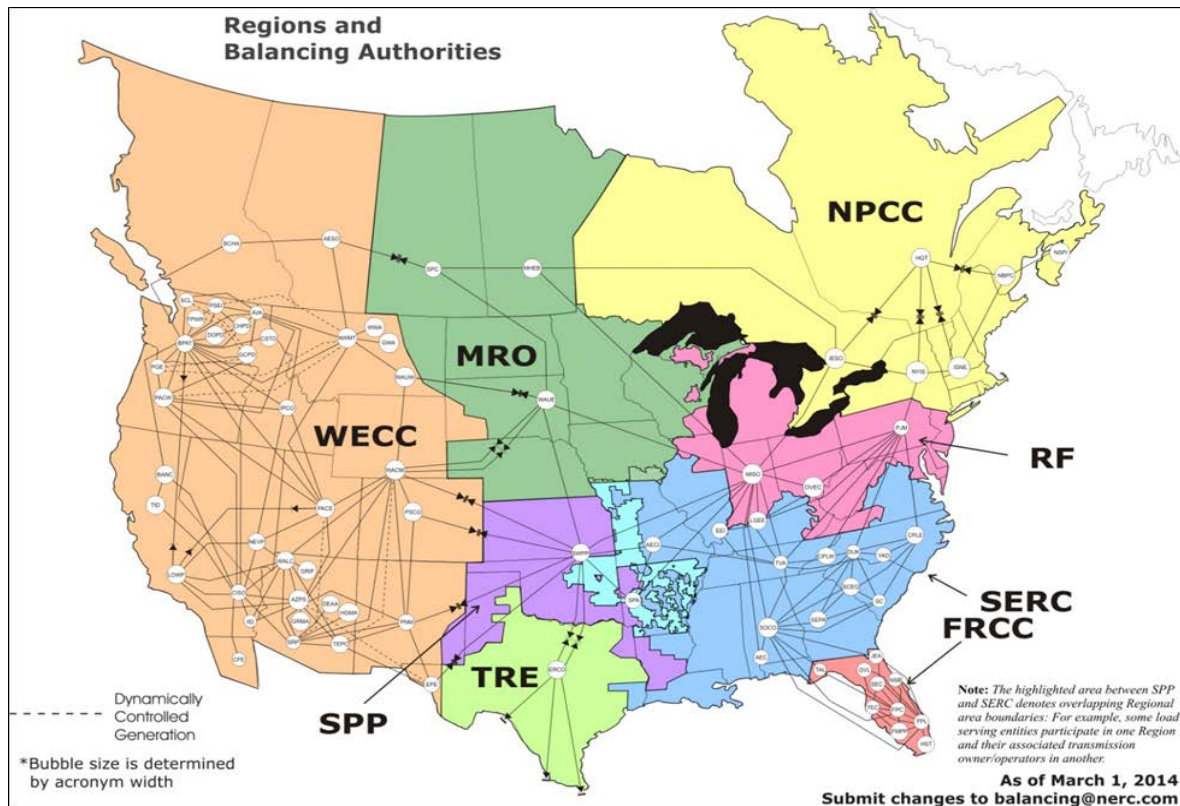


Figure 4.2. Reliability Regions and Balancing Authorities as of March 1, 2014

A wide variety of entities designated as electric utilities operate within this geographic structure, and many non-regulated entities operate in connection with the electric utilities. Because the upper tier structure is geographic in basis, the entire power grid has a rough geographic encapsulation structure (rough because there are specific situations when the geographic boundaries are crossed by certain utility assets or entities; for example, some amount of overlap exists in certain reliability regions due to the fact that distribution companies and their service areas may reside in one reliability region while the transmission companies and some of their assets may reside in a neighboring reliability region).

Architectural Insight 2

The number of Balancing Authority Areas in the US has dropped from well over 100 to about 75 presently, more than 30 of which are in the Western Interconnection. Improved coordination, realignment and possible consolidation of Balancing Authority Areas would contribute to better integration of bulk wind and solar energy with Distributed Energy Resources by improving fast coordination of more widely aggregated assets.

⁶ http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19229.pdf

In addition, electric utilities may have geographically inter-penetrated services areas where significant disaggregation has been pursued, particularly in restructured markets such as Texas (see Figure 4.3).

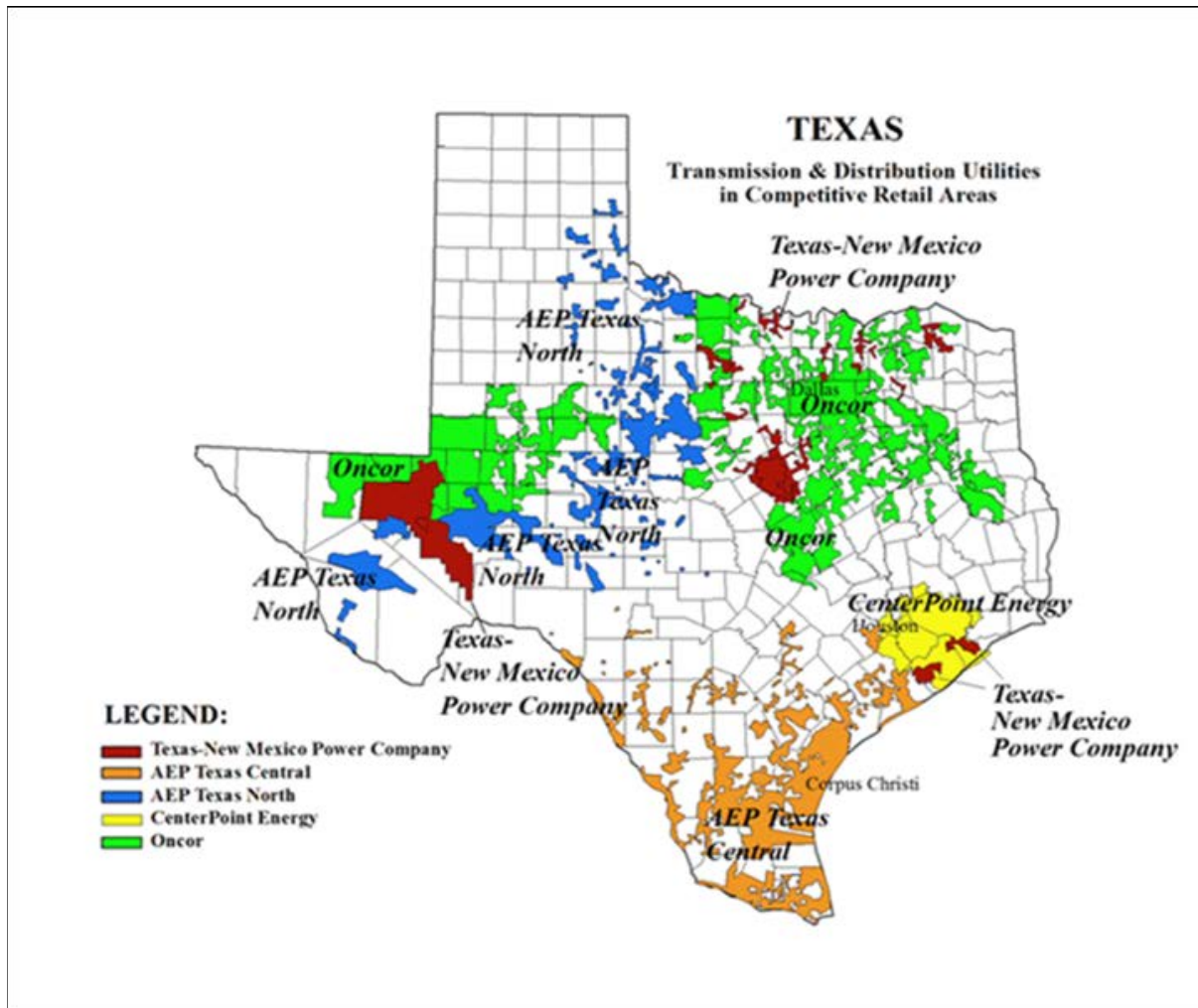


Figure 4.3. Texas Distribution Utility Service Areas

Nevertheless, the geographic encapsulation view is useful as a starting point. Figure 4.4 shows an approximate model for this encapsulation. It is a rough model because there are some exceptions where boundaries are crossed by infrastructure, by business entities, and regulators.

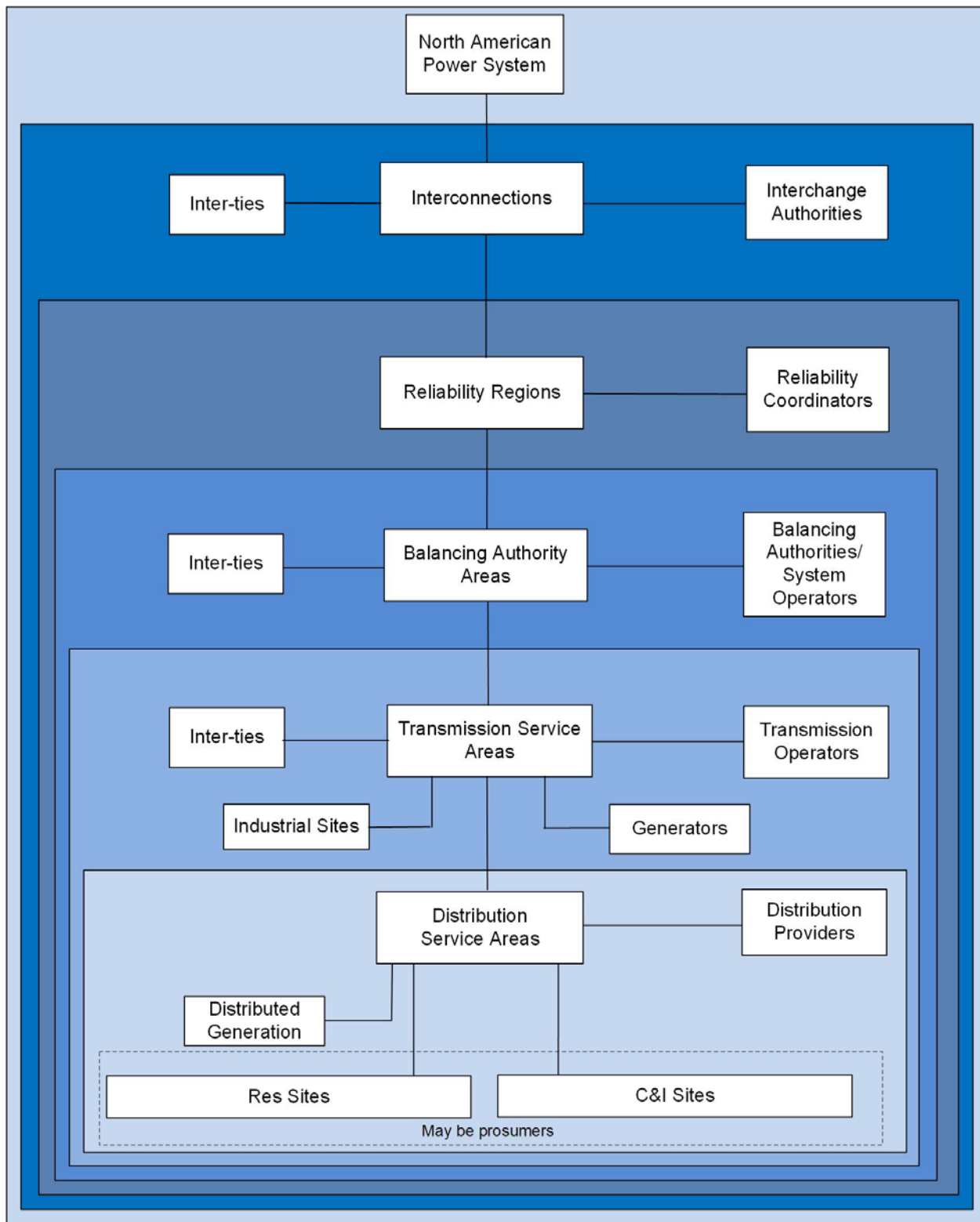


Figure 4.4. Geographic Encapsulation

Architectural Insight 3

The geographic-based structures shown above are artifacts of the evolution of the electric power industry over the past century. Customers and their assets do *not* have to follow any such geographic encapsulation, even for distribution. This can become important as more non-utility assets interact with the grid, raising questions about both reliability coordination and grid control in a merchant DER and prosumer environment.

Policy Implications 1

If customers and the assets they control reside in distinct physical parts of a single region or within distinct geographic encapsulations, and there are physical exchanges (or coordination in the production and consumption of) electricity among them, or with other parties, regulatory issues must be addressed governing aspects of the scheduling and control of the physical exchanges/coordinated actions. An improved approach may include managing assets across jurisdictional lines and include consumers. This will require new regulatory approaches, changes in state and local laws and agreed protocols for communication and interoperability.

4.2 Industry Structures

The utility industry has structure that is closely related to electric system structure and control framework structure, as well as regulatory structure. For architectural purposes, industry structure is represented in Entity-Relationship (ER) diagrams. In such diagrams, each box represents a class of entities and each line represents a relationship between classes of entities. Position of an entity box on the chart has no particular significance; it is the interconnection of entities via relationships that matters here. Note that these are not controls diagrams although some relationships are about various kinds of grid management.

Generally speaking, the models are similar in that they contain the same basic sets of functions: generation, transmission, distribution, retail, etc. They are subject to many of the same emerging trends and issues, although there are certainly regional differences that emphasize the trends differently. Overall, the models are more alike than different but there are important differences, too.

The models differ in terms of whether functions are divided by simple internal organizational boundaries or are split out into separate business entities. In some ways this difference is quite significant, but for operational purposes, especially related to coordination and control, the difference is small: once an organizational barrier is established, it may have to be respected by the control systems whether it is internal or external. It is preferable and often possible to alter organizational boundaries, but for those cases where it is not, the control and coordination framework must be capable of accommodating those boundaries while meeting its primary goals of reliability and safety. The larger issue is how coordination occurs - in the following organizational diagrams the red lines follow the principle lines of coordination and are one of the areas where 20th Century approaches are becoming inadequate for the 21st Century grid.

A second difference is in how utilities are regulated. Regulatory structure for utilities is complex, and some challenges tend to be jurisdictional and hence structural as opposed to rule-based. As pointed out in the previous section, many aspects of grid structure derive from geographic considerations. These structures may merit reconsideration given the emerging changes in generation mix, and the rise of responsive/interactive loads that have differing geospatial characteristics. Due to the relationships between regulatory structure and emerging needs for new types of coordination, the nature of the interplay between regulatory structure and reliability responsibility and management are coming under scrutiny in the industry. As such, clear models for these relationships are needed. The following sections detail models of utilities in various regulatory settings.

4.2.1 Vertically Integrated Utilities

Vertically integrated utilities are found in some regions of the country, notably the Southeast and some parts of the Northwest and Midwest. In such utilities, primary functions are carried out by departments, and various functional system boundaries will be found within the individual utility. Areas dominated by vertically integrated utilities may or may not have wholesale energy or power markets; however, the utility generally will engage in energy transactions with various merchant power producers, markets, and other utilities.

In Figure 4.5, the shaded area represents the vertical utility: generation, transmission, distribution, retail, and balancing. The utility may interact with wholesale markets and various merchant providers. While the utility has many sub-organizations, it has the ability to coordinate across and even modify internal boundaries somewhat more easily than can happen in a disaggregated industry structure.

Vertically Integrated Utility

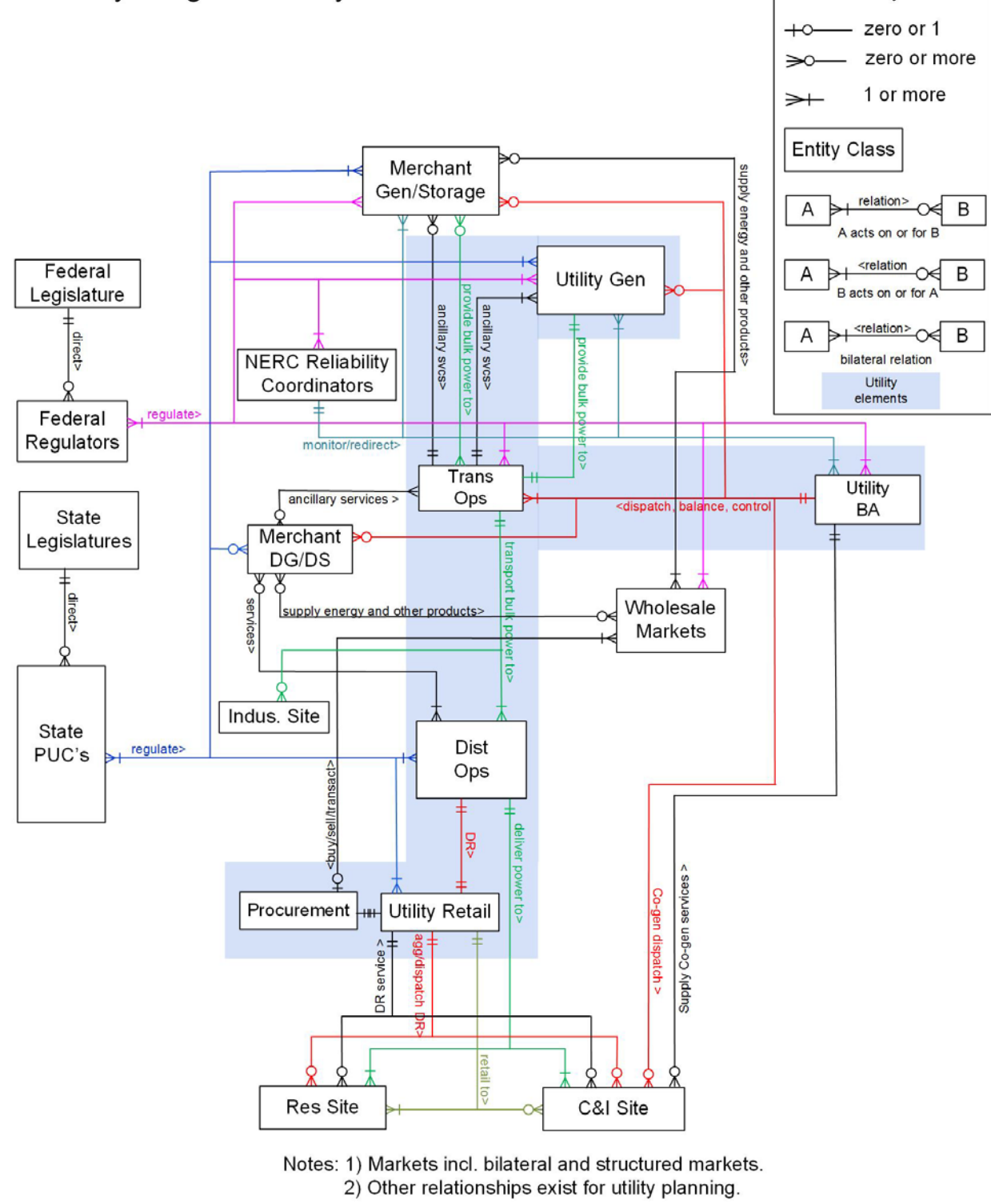


Figure 4.5. Vertically Integrated Structure Model

4.2.2 ISO/RTO-based Utilities

In areas where utilities have been structured for centrally-organized wholesale markets, some functions have been disaggregated and new entity classes have been formed; in particular, the system operators. In regions with wholesale markets, these markets may be operated by the Independent System Operator (ISO) or Regional Transmission Operator (RTO). Additionally, the system operator performs balancing authority functions such as load frequency control (secondary generator control) and dispatch/balancing (tertiary generator control) for balance authority areas. Some ISO's and RTO's have mechanisms to dispatch Distributed Energy Resources (DER)⁷ and Demand Response (DR) assets, including non-utility assets, bypassing local distribution companies ("tier hopping") in the process.

Figure 4.6 illustrates the structure of an ISO/RTO-based utility set. Here there are multiple business entities carrying out functions that would have been handled by departments in an integrated utility. One such entity is the System Operator, which may provide several functions, including operation of wholesale energy and power markets. Transmission Operators may or may not be separate entities from Distribution Providers. The increased number of separate business entities makes the overall structure more complex, and makes it more difficult to modify organizational boundaries and roles than in the integrated case.

⁷ For example, CAISO can dispatch distributed generation that is connected via the Wholesale Distribution Access Tariff Interconnection Process. Facilities with qualifying CHP assign a portion of their capacity to be dispatched by the ISO. ISO-NE defines Distributed Generation assets that can participate in both Forward Capacity and Energy Markets. As another example, PJM has developed the means to dispatch water heater control as thermal storage for use in frequency regulation. This is an example of non-bilateral (asymmetric) storage, because electric energy can be put into storage, but the energy cannot be retrieved as electricity.

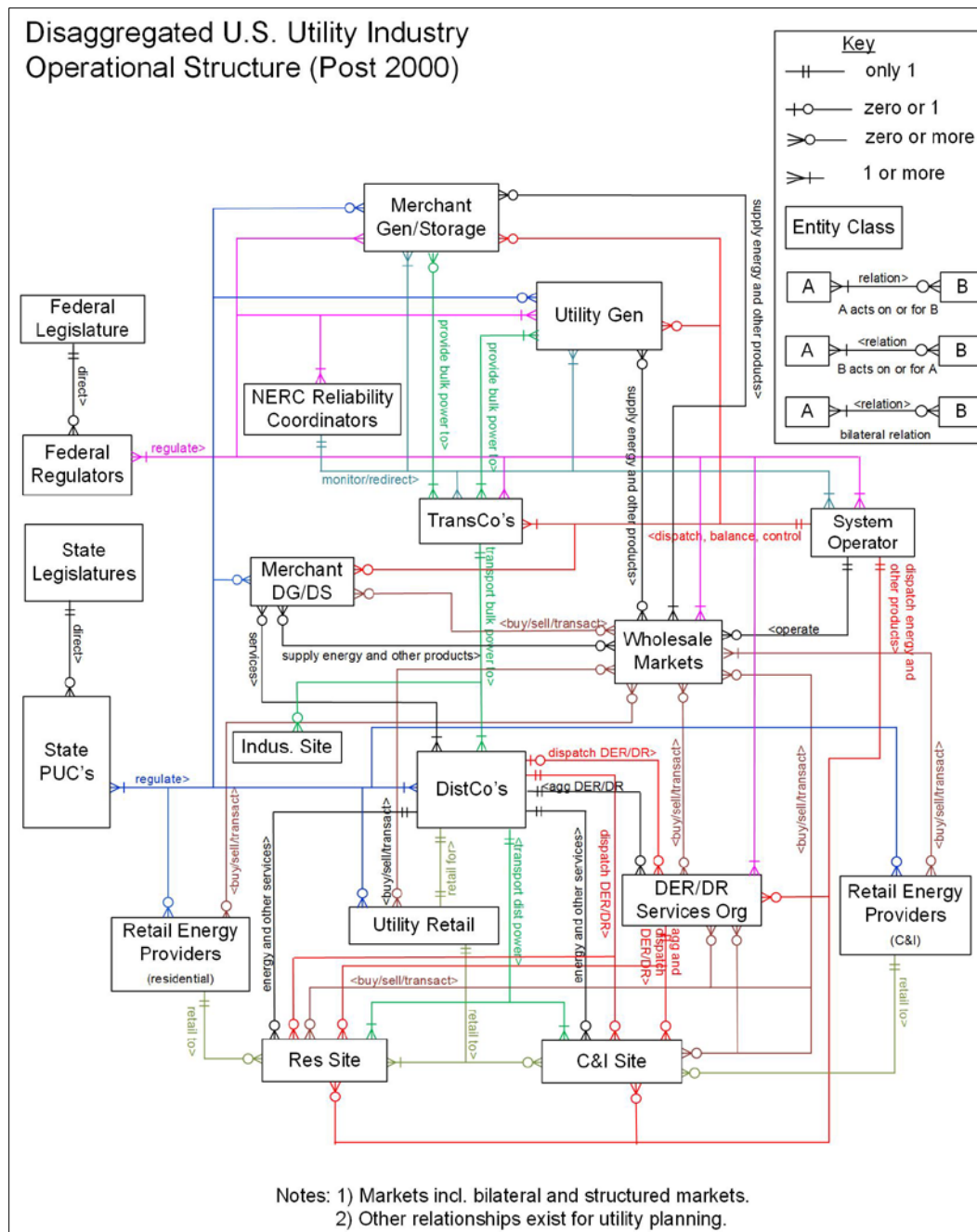


Figure 4.6. ISO/RTO-Based Industry Model

4.2.3 Public Power/Municipal Utilities/Electric Cooperatives

The industry structure models for organizations such as Power Authorities, the Public Utility Districts (PUD's), the municipal utilities, and the electric cooperatives are combined into a single structural model here, due to structural similarities. Figure 4.7 illustrates industry structure for these cases. Note that cooperative, municipal utility or PUD resembles a (partial) vertically integrated utility, with a separate entity or entities for generation and transmission. Collectively, they resemble the ISO/RTO case, with the cooperative or municipal utility being the distribution provider.

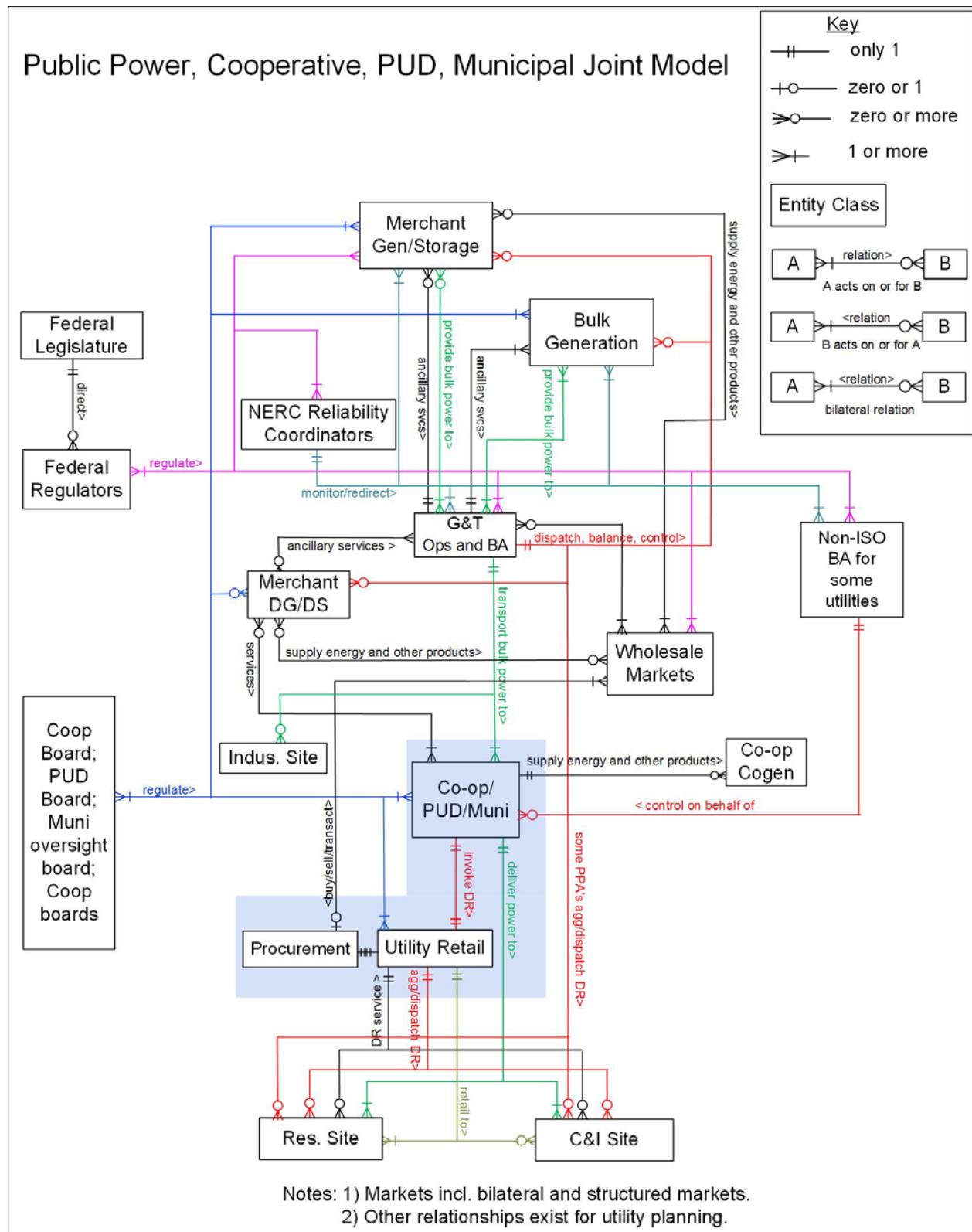


Figure 4.7. Public Power/Municipal Utility/PUD/Cooperative Structure Model

Architectural Insight 4

Note in particular the red lines in the industry structure diagrams. The relationships involved are various aspects of system control, and have direct relationships to reliability roles and responsibilities. Instances exist in the ISO and PUD/Muni/Cooperative cases in particular where bypassing of distribution utilities, instead of working through them in a coordinated fashion, occurs.

Policy Implications 2

The majority of ISO/RTO and some other industry activities at the wholesale level are regulated by the Federal Energy Regulatory Commission (FERC), and industry oversight bodies such as the North American Electric Reliability Corporation (NERC). Investor-owned utility (IOU) and public power/cooperative activities at the distribution level are regulated by state public utility commissions, elected or appointed local boards. Physical and financial exchanges between these separately regulated entities may involve potentially conflicting interactions and/or priorities on the part of Federal and local or state authorities. Moreover, local distribution companies retain the responsibility for maintaining reliability and quality of service at the retail level. However, increasing number of direct interactions with merchant DERs and consumers, while bypassing distribution utilities, adds complexity to the reliability and resilience-related challenges.

4.3 Markets, Services, and Business/Value Stream Frameworks

In addition to industry structure, models for the structure of value streams and related flows are needed to understand the impact of changes to the grid, and to trace the accrual of value from investments made in grid infrastructure. High level versions of these structures are the starting points for such analyses.⁸ In this section, the term “markets” does not mean simply the wholesale energy and power markets, but the entire economic ecosystem around the grid. Also note that in the diagrams, “intelligence” does not refer to data mining of customer usage data or similar issues; instead it refers to understanding of where value resides in the system and how to access it.

Architectural Insight 5

To build value stream models, start with the industry structure diagram, then add the relevant external entities that may participate in the business ecosystem. The resultant flow models can be recursively detailed, and the placement of any investment or new value stream in the architectural model can be analyzed in context to determine such issues as where value accrues, what value stream share may be available, and how a value stream supplier should be coupled to its ecosystem partners.

⁸ Figures 4.8 through 4.11 were created by and are used here courtesy of Paul De Martini, Newport Consulting, as is much of the discussion in Section 4.3.

4.3.1 Value Stream Structure for Vertically Integrated Markets

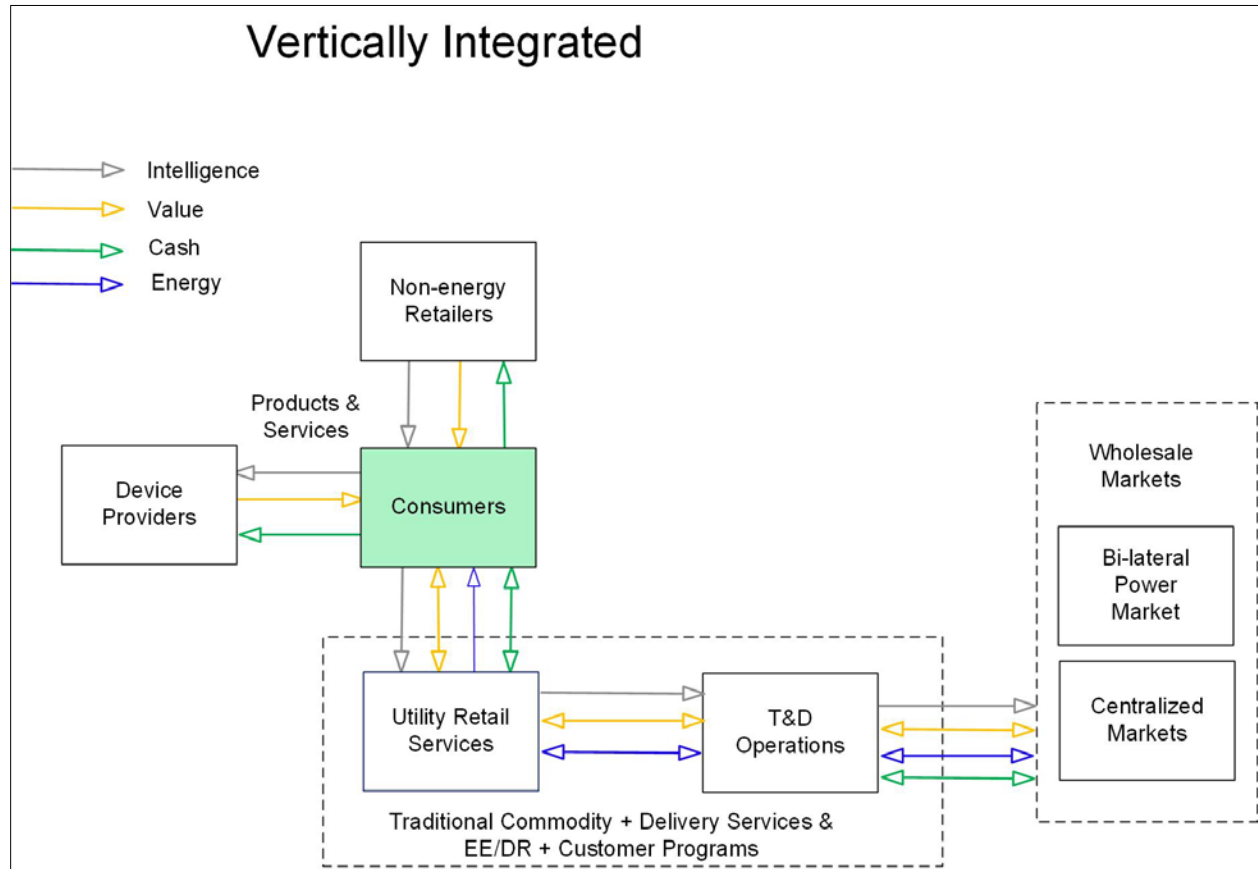


Figure 4.8. Vertical Integration Value Stream Structure

4.3.2 Value Stream Structure for Hybrid Markets

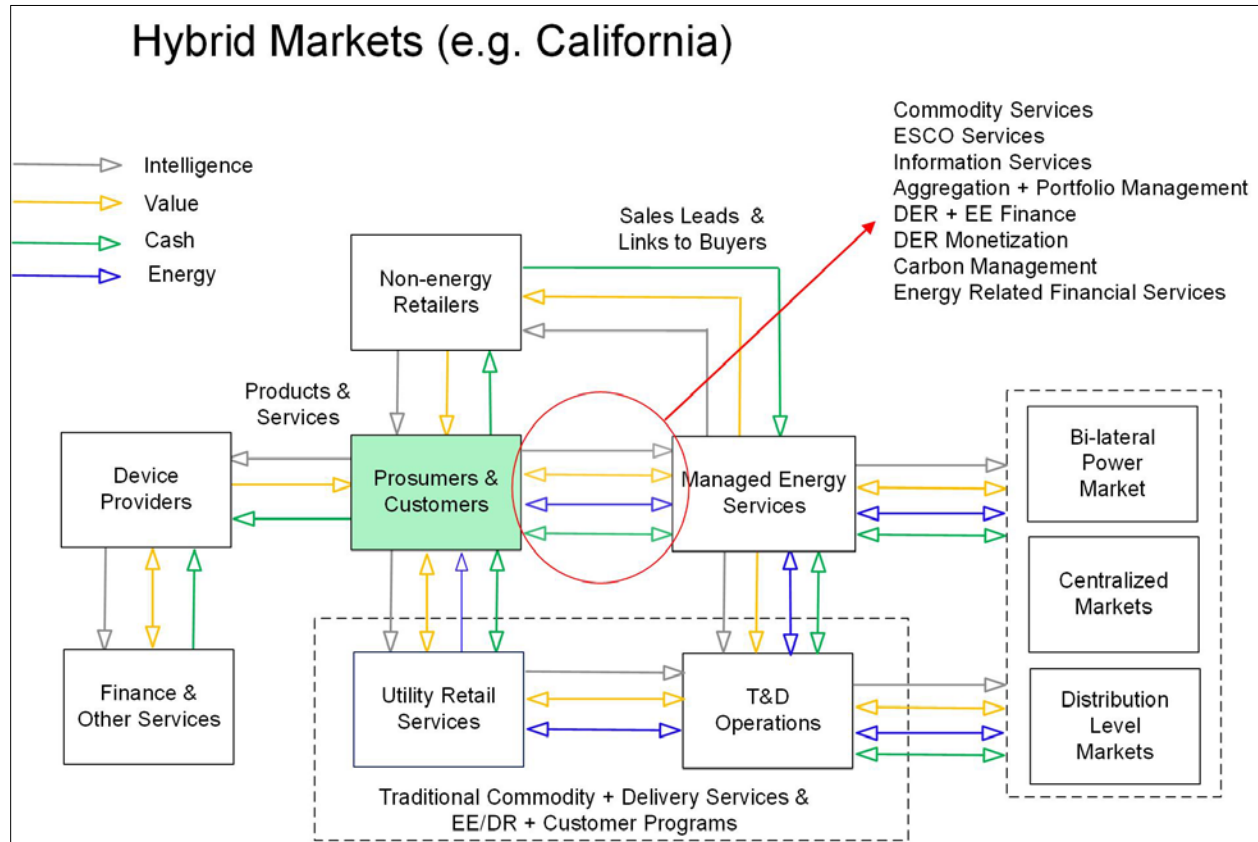


Figure 4.9. Hybrid Markets Value Stream Structure

4.3.3 Value Stream Structure for Texas

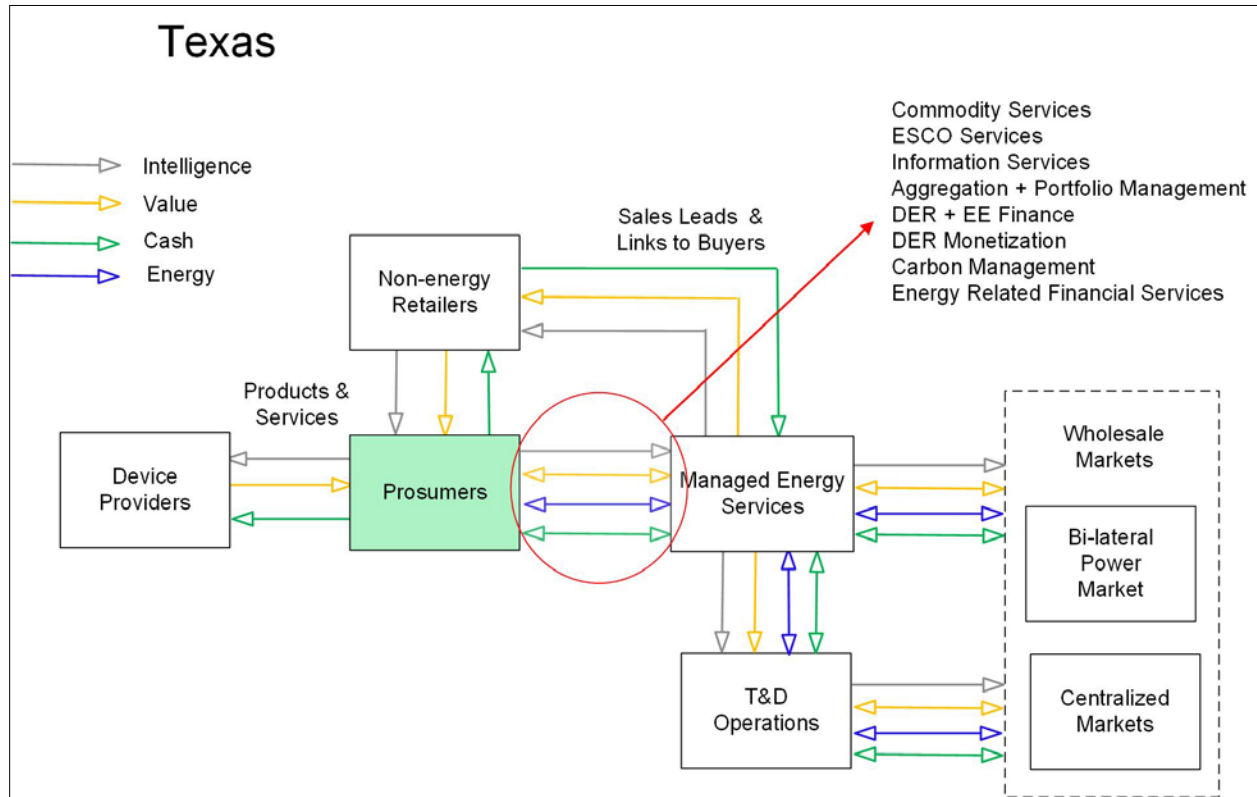


Figure 4.10. Texas Value Stream Structure

4.3.4 Value Stream Structure for Independent Aggregator Markets

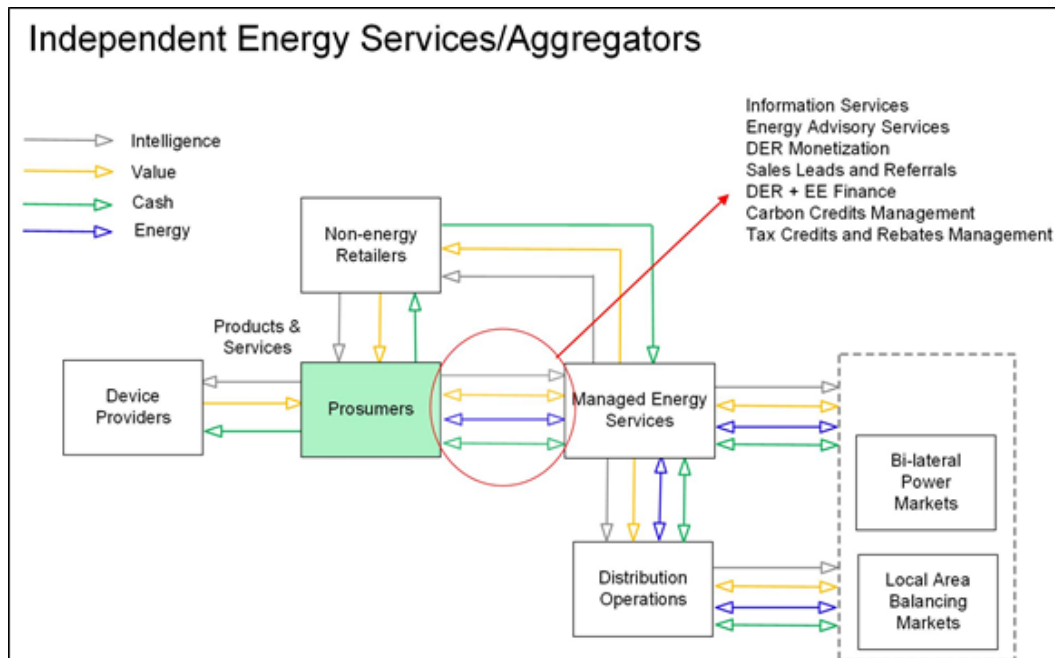


Figure 4.11. Energy Services/Aggregator Value Stream Structure

Architectural Insight 6

It is practical to partition value stream sources (e.g. products and services) into those with high growth and value production potential, and those with limited potential. With the exception of the customer/prosumer, any box that touches a commodity stream (blue arrows) should be considered within the limited potential category, because optimization of the energy stream is essentially a zero-sum proposition. This means that value shifting can occur between entities, but opportunities for new value creation are limited, at best. In fact, some new device providers (such as solar PV leasing entities) prefer to be classified as offering “net load” rather than as energy producers, in order to stay on the non-regulated side, away from the commodity streams. The main reason is that state regulatory interconnection rules usually pass interconnection costs for customer side connections to all customers - whereas merchant DER has to pay for the interconnection costs solely. In addition, the merchant DER providers wish to minimize the amount of regulation they encounter.

4.3.5 Value Attachment

Services associated with storage attach to different industry entities in the sense that value is determined by those entities, based on the services and their unique requirements. In fact, this is true of grid services in general, no matter how they are delivered. The industry structure diagram provides a means to understand this issue, as shown in Figure 4.12. In this diagram, sets of services are attached to the entity class that determines their values. Note that in a few cases, value may be determined in more than one place.

Disaggregated U.S. Utility Industry Operational Structure (Post 2000)(Partial)

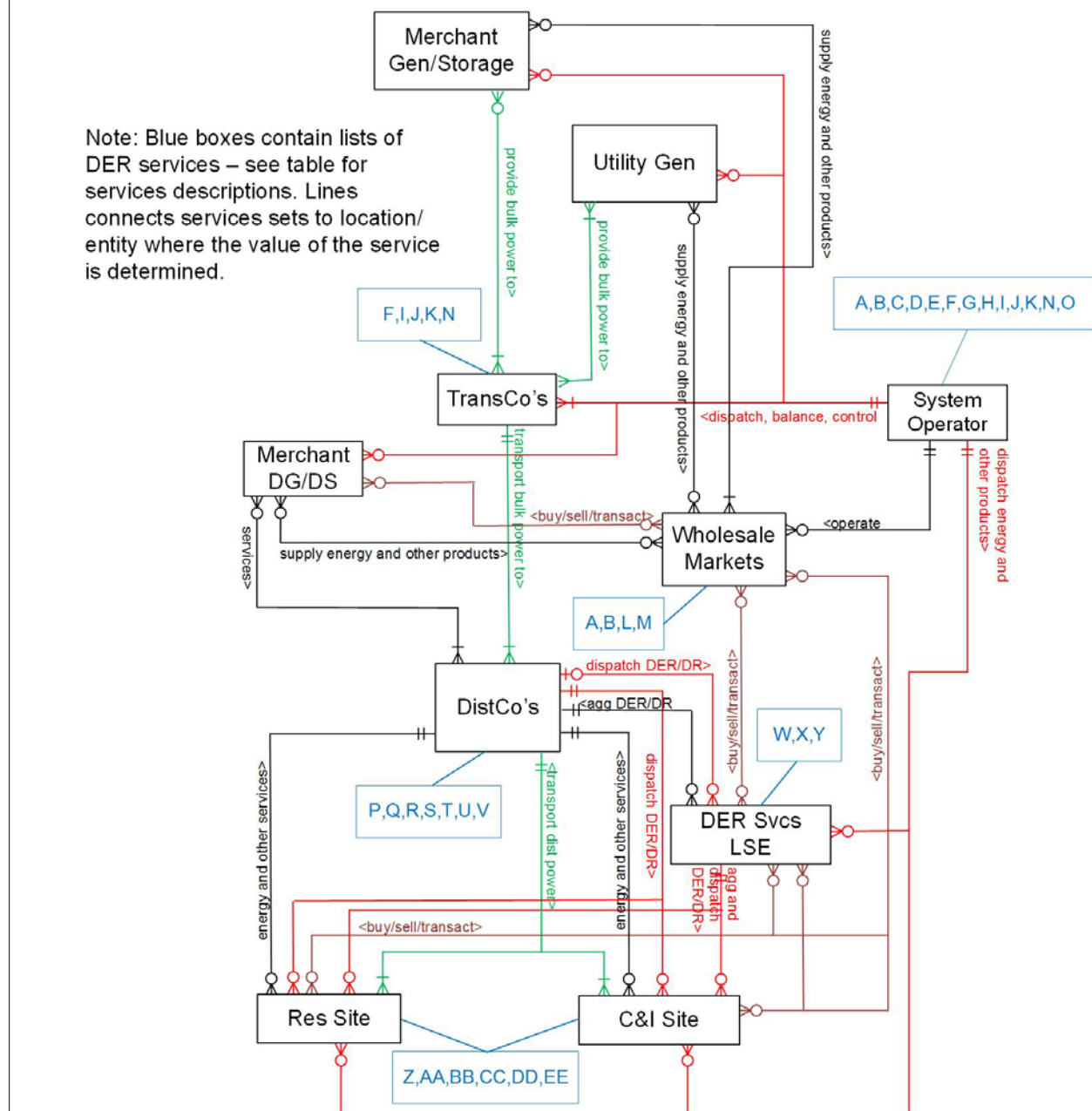


Figure 4.12. Value Attachment in ISO/RTO-Based Markets

Table 4.1 below defines and characterizes the services, based on studies from Sandia National Laboratory⁹ and Southern California Edison.¹⁰

⁹ Sandia National Laboratory, "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide", 2010

¹⁰ Southern California Edison, "Moving Energy Storage from Concept to Reality", 2011

Table 4.1. Power System Services Definitions and Properties

Power, Transport & Related Value Categories						
		Reference No.		Control Coupling	Monetizable	Market Method
Bulk Power System		SNL	SCE			
A	Consumption time shifting	1	1	L	Yes	Bi-lateral market, demand response programs
B	Electric supply capacity	2	1	N	Yes	Bi-lateral market
C	Electric supply reserve capacity	5		L	several places	Forward auctions
D	Load Following (Ramping)	3	3	T	No	in development
E	Control area regulation	4	3	T	Yes	
F	Transmission Voltage Regulation	6	3	T	Yes	
G	Frequency Regulation		3	T	Yes	
H	Black start provision		4	T	Yes	
I	Transmission congestion relief	8		T	Yes	Real-time Market Price
J	Transmission support/reliability	7		L	Yes	
K	Transmission upgrade deferral	9	5	N	Yes	Alternatives Procurement
L	Intermittent energy firming	16	1	L	Yes	Bi-lateral market, Procurements
M	Electric energy shaping		2	L	Yes	Bi-lateral market
N	Intermittent renewables integration	17		L	Yes	Alternatives Procurement
O	System inertia			T		
Distribution System						
P	Distribution upgrade deferral	9	6	N	No	Procurement for Alternatives
Q	Distribution power quality (voltage)			T	No	Tariff service
R	Distribution overload mitigation		7	T	No	Demand Response programs, Procurement for Alternatives
S	Distribution asset optimization			L	No	Tariff service
T	Intermittent distributed generation mitigation		9	L	No	Procurement for Alternatives
U	Distribution resiliency			T	No	Procurement for Alternatives

V	Distribution reliability	13		T	No	Procurement for Alternatives
Load Serving Entity						
W	Electric energy/load shaping			L	Yes	Bi-lateral market, imbalance market
X	Price/Volumetric risk management			N	Yes	Bi-lateral market
Y	GHG management/reduction			N	few states	Carbon market, Renewable credits
Customer						
Z	Energy cost (Price & Volume) management	11		N	Yes	Tariff, Bi-lateral retail market, demand response & energy efficiency programs
AA	Customer retail rate optimization	12	10	N	Yes	Tariff
BB	Service reliability enhancement		11	T	Yes	Tariff Service, Asset Purchase/Lease
CC	Uninterruptable power supply		12	T	Yes	Tariff Service, Asset Purchase/Lease
DD	Enhanced power quality	14	11	T	Yes	Tariff Service, Asset Purchase/Lease
EE	GHG management/reduction			N	few states	Carbon market, Renewable credits
Control Coupling Legend: T =Tight, L = Loose, N = None						

4.4 Electric Structure

Electric grid structure is strongly related to industry structure; and like industry structure, it has to some extent grown up organically with the electrification of the country over the course of last century. Traditional electrical structure may be summarized as follows: one-way energy flow from central station generators, over a transmission network, through substations onto distribution systems, over radial distribution circuits to end-use customers. Figure 4.13 below provides a basic model for grid topology.

At the bulk system level, circuits are strongly meshed. Distribution primary circuits are mostly simple radial trees, with some amount of interconnection in limited cases, and some amount of looping in some designs. Dense urban distribution is a special case discussed later, with highly meshed distribution secondaries fed at mesh corners by primary feeders. Not shown on the diagram is the fact that for radial distribution feeders, wire sizes may decrease with distance from the substation. This means that such feeders have less capacity for handling DER at the far ends of the feeders than they do nearer the substations.

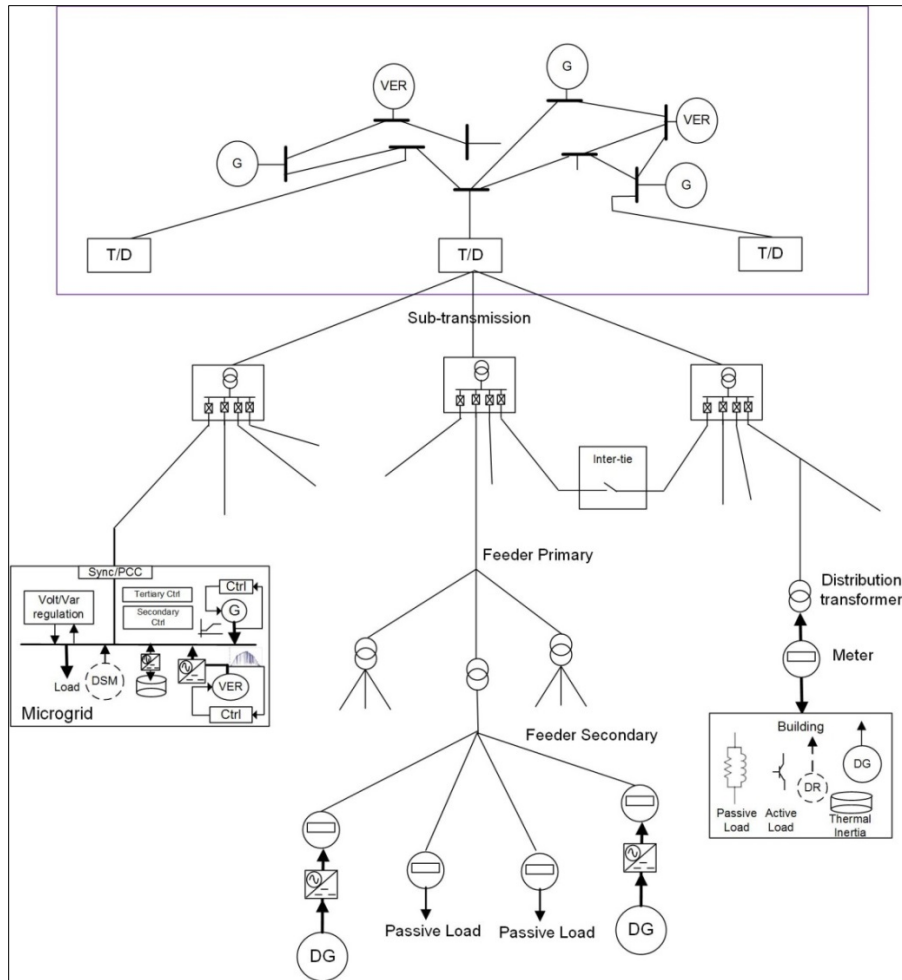


Figure 4.13. Basic Electric Structure

Many of the recent changes to power grids have been conceived and built organically and in a bottom-up manner, as opposed to being designed from a systems standpoint, partly due to the enormous legacy investments in infrastructure. It has led to a situation where system stability has been a result of large design and operating margins, as opposed to joint economic/control design. Such margins have been decreasing and the resulting systems may, in fact, be chaotic.¹¹

¹¹ Peter Fairley, "The Unruly Power Grid," IEEE Spectrum, August 2004, pp. 22-27.

Architectural Insight 7

In the chaos theory view of grid stability, the seeds of wide area blackouts and other manifestations of instability *are inherent in basic grid structure*. This viewpoint, which is not universally accepted, arose even before the recognition of stochastic generation and reduction of grid inertia as destabilizing influences. However, time and again, **the structure of the grid determines important system properties and basic limits**.

Policy Implications 3

Responsibilities for reliability management have historically been established hierarchically, starting with wholesale generation/transmission treated in a semi-integrated fashion, but then separately at a lower level within distribution—where reliability requirements have historically been assigned to single regulated entities. As previously noted, two-way flows within distribution systems will require greater focus on making more explicit shared responsibilities for reliability management (and supporting investments) between distribution system operators and loads/producers within that distribution system.

Key Question 2

What is Generation Bifurcation?

This term refers to the emerging split of generation between bulk transmission-connected generation and smaller distribution-connected generation, such as rooftop solar PV, CHP, and microgrid generation.

4.4.1 Transmission/Bulk Power System Structure

While some radial transmission lines exist, the bulk power system for the most part is partially meshed. The IEEE 118 Branch and Bus model shown in Figure 4.14 is an example of this partial meshing.

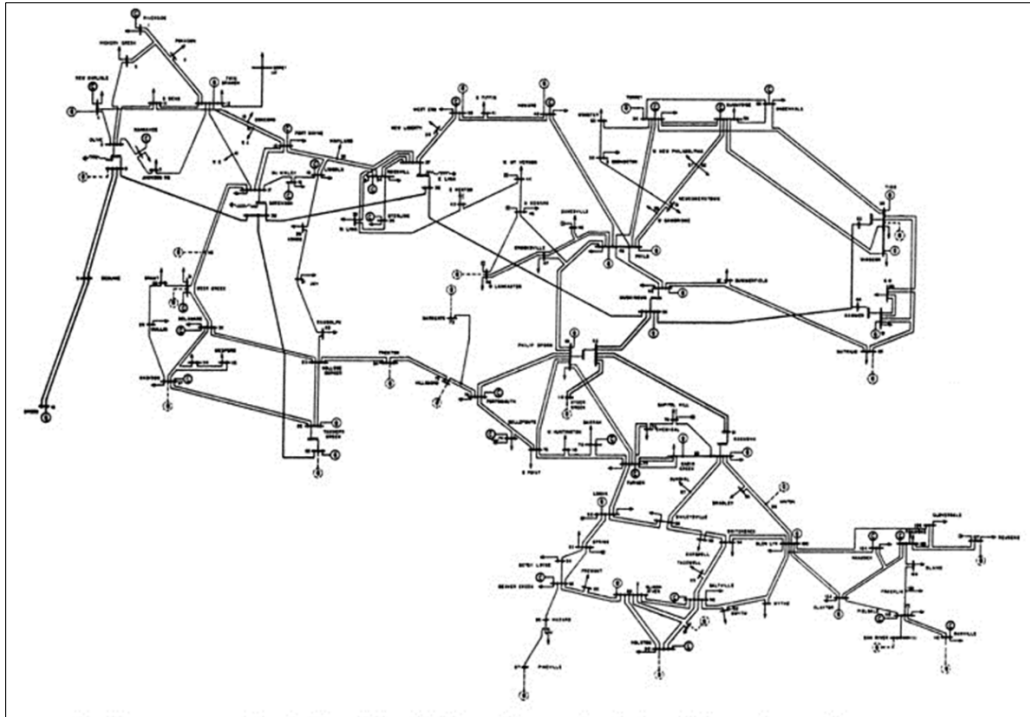


Figure 4.14. Transmission Circuit Meshing

4.4.2 Primary Substations

Transmission and distribution substations both have internal structure that may exist in any of several forms. The more common forms are illustrated in Figure 4.15 below. Most of these arrangements allow for use of multiple power transformers, and for isolation of individual transformers and bus sections. This provides for improved robustness in the face of transformer or bus faults, or attacks on substation equipment. Many primary substations contain more than one power transformer, sized so that one transformer can handle the full load if necessary.

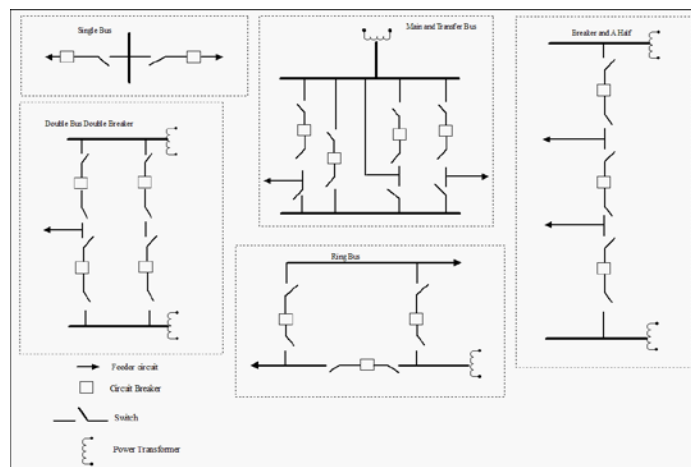


Figure 4.15. Substation Bus Structures

Note that, configuration issues aside, feeder circuits are grouped and connected to substation buses. This is the mechanism for electric coupling in the substation, and is a cause of unwanted interactions between distributed generation connected to distribution feeders and protection elements (breakers) in the substations. These interactions can lead to sympathetic tripping of one circuit breaker due to a fault on a different feeder.¹² Many other detrimental impacts of DER due to electric coupling have been identified,¹³ leading to an understanding that reducing or eliminating constraints imposed by distribution grid electric circuits (i.e., making *structural* changes) is an appropriate focus for grid architecture.

4.4.3 Distribution Circuits

Most US distribution circuits outside of dense urban areas are radial, with some amount of branching and laterals. In non-rural areas, it is not uncommon to see some interconnection of feeders via inter-tie switches (manual or remote controlled) for the purposes of re-routing power after sectionalizing a portion of a feeder circuit for fault isolation or for maintenance work as shown in Figure 4.16 below.¹⁴ The structural change from simple radials to sectionalizing and selected inter-ties was necessary to enable “self-healing” distribution circuits. However, with the exception of circuit sections that can be switched from one feeder to another via inter-ties, real power flow was designed to move in only one direction and was confined to simple tree-structured flow, along lines of decreasing diameter as a function of distance from the substation. Key characteristics and issues at the distribution level that are driving DER integration complexity include:

- Radial circuits have unique technical characteristics that differ from circuit to circuit
- Distribution three phase circuits operate in unbalanced fashion and most DER is connected to a single phase of the three phase feeder

¹² P. Barker, T. Short, T. Key and F. Goodman, “Engineering Guide for Integration of Distributed Generation and Storage into Power Distribution Systems,” EPRI Technical Report 1000419, December 2000.

¹³ R. A. Walling, et. al., “Summary of Distributed Resources Impact on Power Systems,” *IEEE Transactions on Power Delivery*, Vol. 23, No. 3, July, 2008.

¹⁴ T. A. Short, *Electric Power Distribution Handbook*, CRC Press, 2004.

- Distribution feeder circuits are frequently reconfigured for various purposes, including maintenance, flow balance, and fault isolation and service restoration

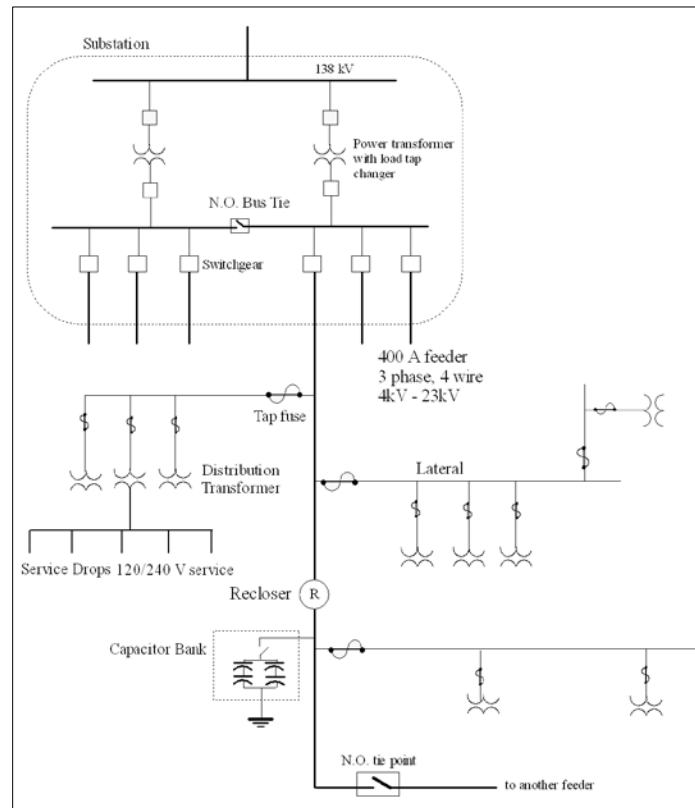


Figure 4.16. Typical Radial Feeder Structure

Ordinary distribution circuits have a two-tier structure. The upper tier is the feeder primary, a three phase circuit operating at medium voltage (4 kV to 36 kV, most commonly 12 kV or 23 kV). The feeder may have branches. Laterals may also branch off from the feeder primary, and these may be one, two, or three phases, but are most commonly single phase. The second tier is known as the feeder secondary, and consists of circuits on the secondary sides of distribution transformers (each distribution transformer has a secondary circuit). In the US, feeder secondaries typically serve five to seven residential loads, although in rural areas it is usually only one load per secondary, and may serve eight to nine loads in some places. Most distribution transformers have single phase secondaries, although three phase distribution transformers exist. When three phase service is needed, it is common to group single phase distribution transformers in threes. While feeder primary circuits are mostly radial, there are looping arrangements as well. Figure 4.17 below¹⁵ illustrates some commonly used distribution loop arrangements. In Figure 4.17, blue boxes represent power transformers in substations, yellow boxes represent fuses, and the green and red boxes represent switchgear.

¹⁵ Source: “Distribution Systems, Substations, and Integration of Distributed Generation”, John McDonald, et.al. Electrical Transmission and Smart Grids, Springer, 2013.

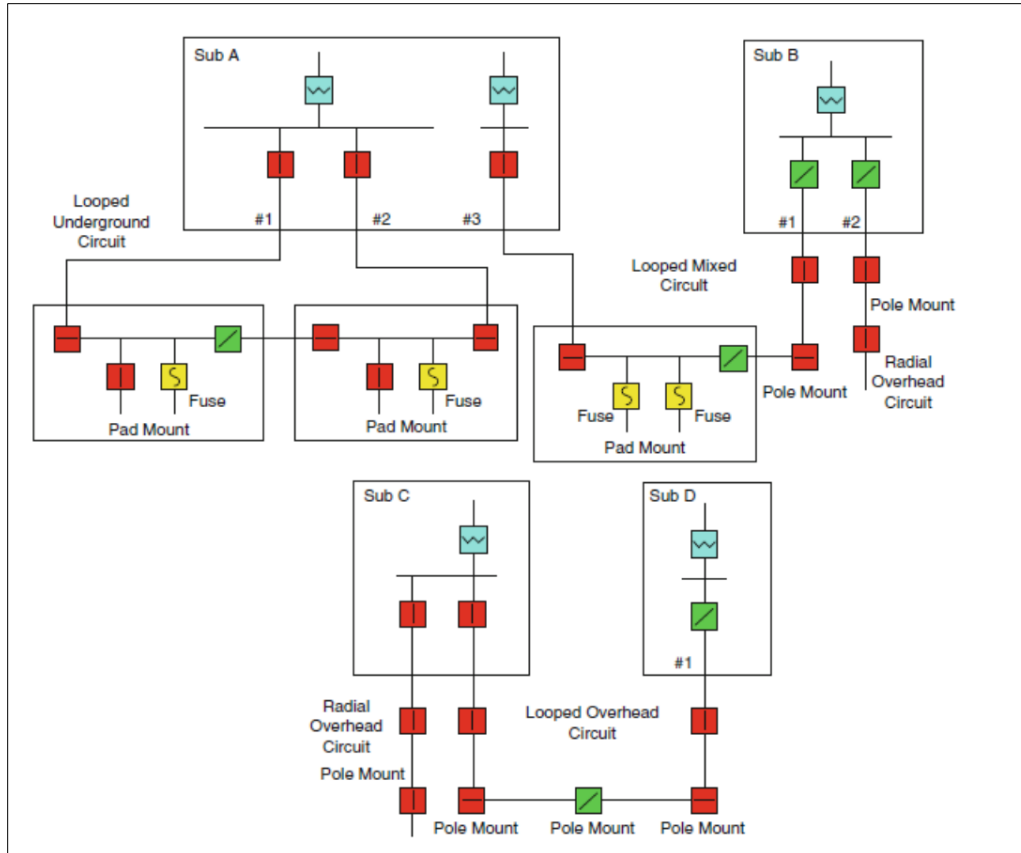


Figure 4.17. Common Distribution Looping Arrangements

In highly dense urban areas (e.g., Manhattan and many other major urban centers) a dense underground mesh distribution system is used as shown in Figure 4.18 below.¹⁶ This type of grid uses special components (network transformers, network protectors) to connect distribution primary feeders to a regular mesh structure that feeds the buildings. The secondary in this case is a mesh network, fed at many points by distribution primary feeders. The purpose of the network protectors is *to prevent the reverse flow of power from the mesh back into the network transformers*.

¹⁶ Source: Engineering Guide for Integration of Distributed Generation and Storage Into Power Distribution Systems, Electric Power Research Institute, 2000.

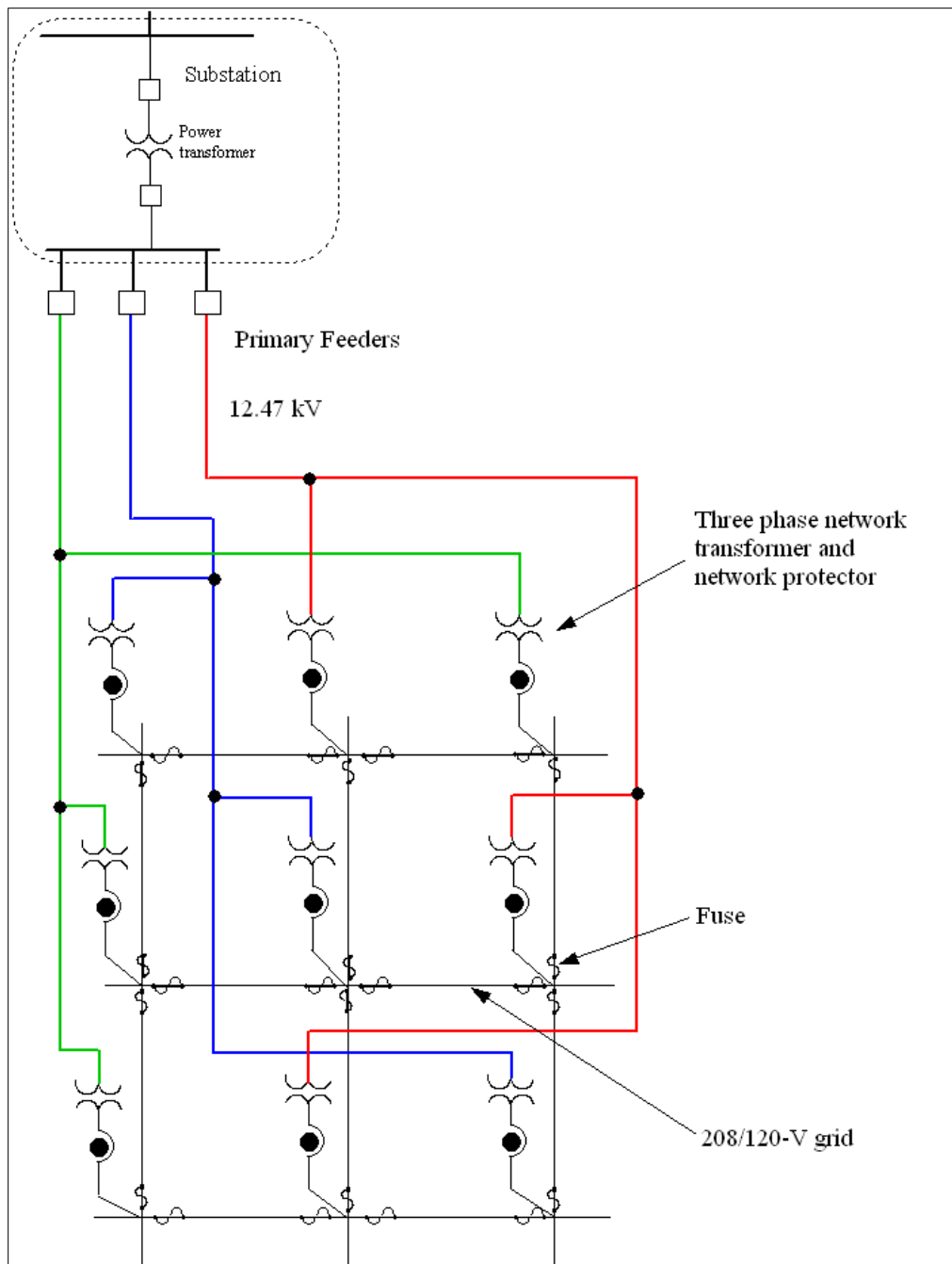


Figure 4.18. Dense Urban Distribution Circuit Mesh

In smaller urban areas, a variation known as a spot network is used rather than the dense mesh pictured above; however, it also makes use of network transformers and network protectors.

Architectural Insight 8

The structure of the dense urban mesh limits any services that buildings might supply to grids except for those that reduce net load and thus do not attempt to put power back into the grid. In these contexts, DG and storage cannot push power back into the mesh primary distribution feeders, and thus cannot push power to the grid. Furthermore, tripping of multiple network protectors can cause a portion of the secondary mesh to island (separate from the rest of the grid). Since the network protectors are not coordinated, the extent of the island is unpredictable. Where fuses are used in the secondary, some of these may blow, requiring truck rolls to replace before normal operation can be restored.

Policy Implications 4

The enablement of two-way flows within distribution systems in the face of structural limitations such as described above can have costs that go beyond those related to new premises equipment and software. Some amount of change at the utility level may be needed just to unblock the potential for certain building-to-grid energy/power services.

4.5 Basic Electric Coupling Model

Coupling in electrical grids is the interconnection and interaction of elements in ways that may be planned and useful, or may be unplanned and harmful. The most basic form of coupling in the grid is direct electric interconnection. This occurs at many levels, as shown in Figure 4.19. The red lines indicate principal paths of electric coupling. Some of these paths are not only useful, but necessary, whereas others were inconsequential until emerging trends like penetration of distributed generation started to raise the issue of unintended behavior.

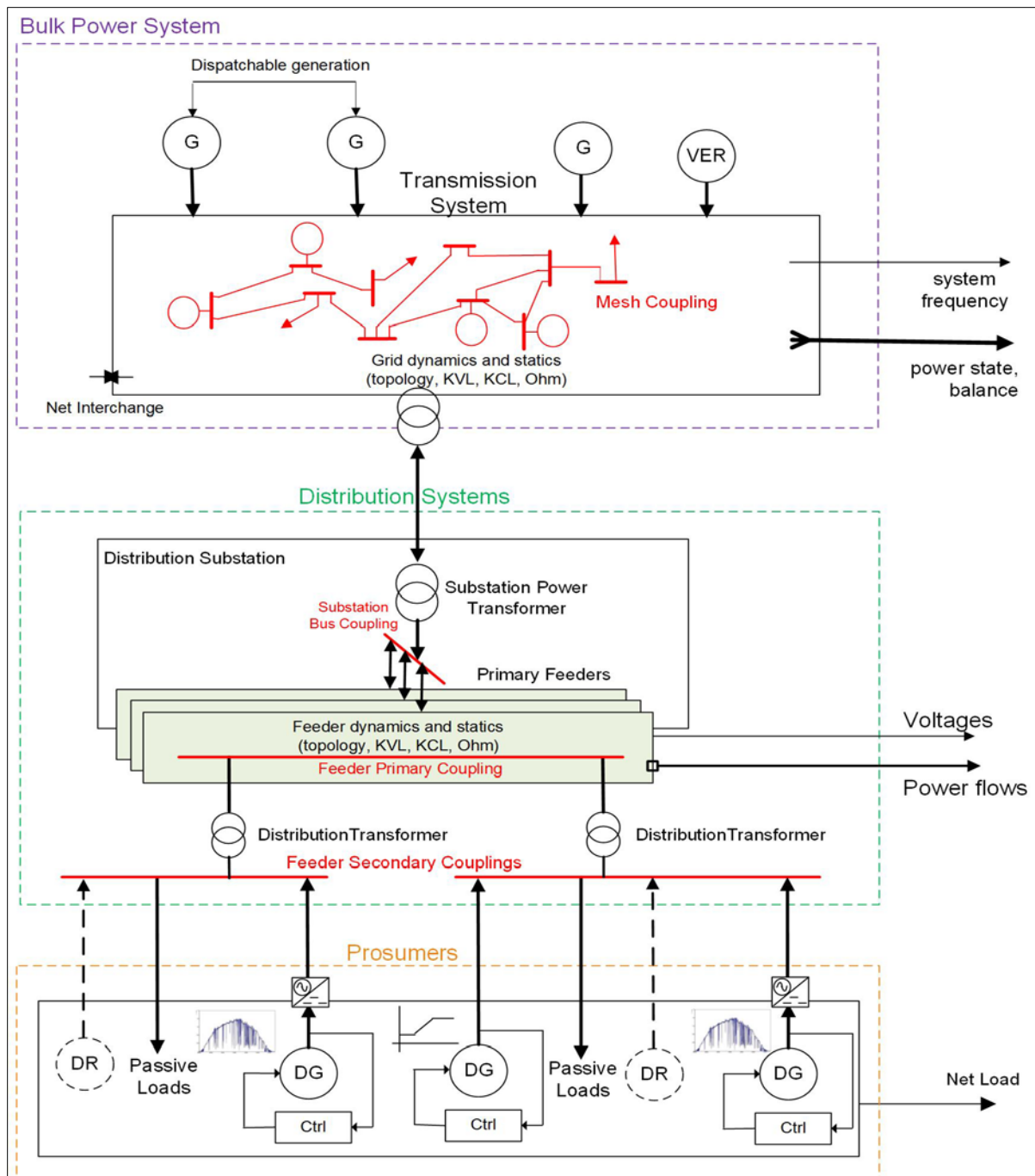


Figure 4.19. Basic Direct Electric Coupling

Architectural Insight 9

While basic coupling occurs electrically at multiple levels in the grid, coupling can and does occur in other ways, some of which can be quite subtle.

Coupling can occur through controls, markets, communications networks, fuel systems, loads, and social interactions of customers/prosumers. Unsuspected coupling is a hazard of increasing grid complexity.

Even basic electric coupling can have subtle consequences. DG with reverse power flow on a radial feeder can cause false circuit breaker trips on that feeder due to a fault on a *different* feeder connected to the same substation bus. DG can also interfere with breaker/fuse coordination. On dense urban meshes, DG can cause unintentional islanding due to tripping of network protectors (islanding is not just for microgrids— DG can cause or support islanding in a variety of ways). The list of interactions is growing as the penetration of new devices and functionality increases.

4.6 Dynamic Interaction Model

Due to the complexity of grid interactions caused by coupling, it is becoming unsustainable to modify one part of the grid without understanding whole grid effects and implications. Some recent examples of new understanding about grid interactions include the interaction of Demand Response and Volt/VAr regulation on distribution grids, and the rising concern about the impact of reduction in grid inertia on various aspects of grid stability. In addition, the bifurcation of generation and the rise of transactive loads are changing the basic assumption about distribution being a passive load on transmission. The interaction model in the figure below illustrates the dynamic impacts of basic coupling as shown in the electric coupling model.

Note that the dynamic model includes a block labeled system inertia. This is the sum of rotational inertias exerted by the various rotating machine generators connected to the transmission grid. This inertia acts as a stabilizing influence and is in fact a crucial element of primary generator control in bulk power systems. The combination of generation with droop control, system inertia, and coupling through transmission not only tends to stabilize against small signal oscillations but also reduces the tendency of generators to “hunt” when finding a new load sharing equilibrium after an incremental load or generation change. This is an example of a desirable coupling effect and it can be compromised by the on-going

reduction of system inertia being caused by the replacement of traditional generators with those that have little or no inertia (wind and solar).¹⁷

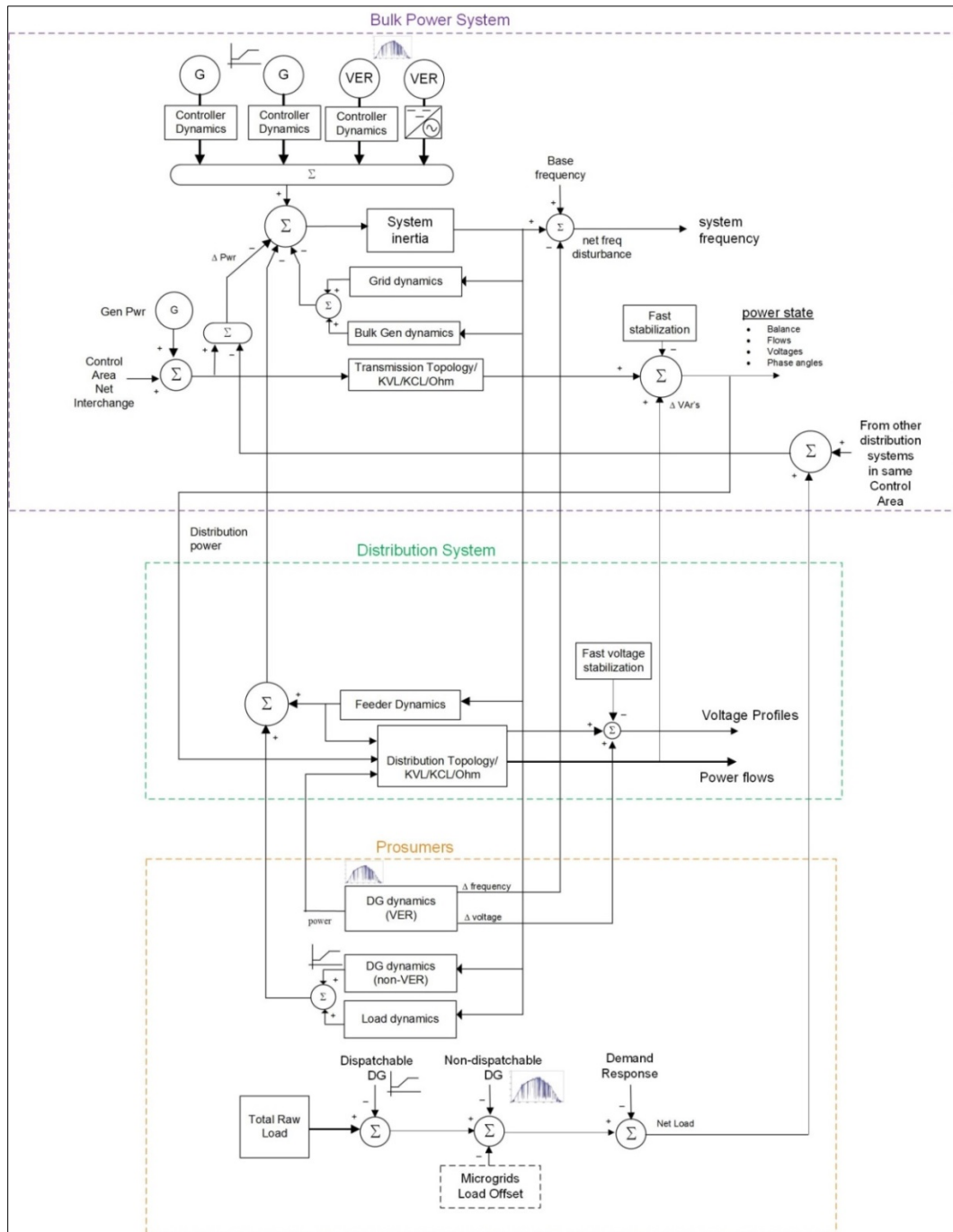


Figure 4.20. Grid Coupling Structure

¹⁷ Figure adapted from small signal grid dynamic model in *Electric Power Systems Analysis and Control* by F. Saccomanno, John Wiley and Sons, 2003.

Architectural Insight 10

System inertia and coupling (interaction) of generators with droop control through the transmission system are crucial to proper present-day grid operation. Other methods are possible but the majority of existing generators use this method. The gradual reduction in system inertia caused by replacing traditional generation with wind and solar will cause gradual degradation system stability.

System inertia is not just a single value for a whole interconnection. For example, in the Western Interconnection, loose coupling means that the effective inertia in one area as seen by the generators there is different from that seen in another area of the same Interconnection. The Western Interconnection is also the one where most of the system inertia reduction trends due to the shift to wind and solar generation are presently evolving. Measurement of system inertia to track changes must be done in multiple locations in the Western Interconnection in order to understand the implications of changing generation mix.

Other emerging causes of instability include “hiding” of bulk system reserve requirements due to the existence of DER that can change rapidly, and lack of coordination between DER operations and bulk system operations.

Policy Implications 5

Exploring methods for measuring—and potentially predicting—system inertia associated with existing operations as well as in the context of a changing generation mix may provide key insights for policymakers and regulators concerned with system reliability. At present, this may require additional R&D efforts. In addition, such methods would be useful in the development of joint planning tools, which likewise do not yet exist for purposes of enhancing industry and policymakers’ understanding of emerging infrastructure interdependencies (such as electricity and natural gas). Meanwhile, efforts underway in ERCOT to consider inertia-related grid services merit careful attention. As discussed more fully below, novel configurations of assets at the distribution level (including storage) may ultimately be leveraged to help provide such services—but once again, regulatory friction associated with determining which entities are eligible to provide such services, and allocation of costs and benefits, may arise under current law.

4.7 Control/Coordination Framework

While individual elements of grid control are well-known, a whole grid control model is not widely available. However, as the coupling models show, the grid has become too complex to treat in siloed sections. Control is crucial for obvious reasons (it causes the business outcomes to happen) and it is also a source of coupling. Existing grid controls have been developed in the context of 20th Century design criteria, most of which are being altered for the grid of 2030.

Any whole grid control framework must encompass a range of elements: primary, secondary, and tertiary generator controls, balance and dispatch, load frequency control, flow control, regulation of voltage and reactive power, stabilization (counteracting disturbances), and synchronization (since the grid is AC based). Control is divided across many entities and the process of aligning control (coordination) must take into account the structure of control in the whole grid. The figure below combines bulk system control, transmission and distribution level control, and elements of non-utility assets that are transactive with the grid or otherwise impact grid behavior in more than a passive load mode.

The system control level illustrates how system control is integrated with wholesale markets (basically the 15 minute and 5 minutes markets are part of the optimizing steps in receding horizon controls).¹⁸ Even the day ahead market (where it is used) is part of a control loop, since absent any bidding into the 15 or 5 minute markets, a settlement in the day-ahead market specifies a dispatch schedule that the generator is bound to meet.

The control structure model does not specify control algorithms or laws, but does indicate lines of control, especially those that cross entity boundaries. Localized control is also indicated. At the distribution level, three different modes for Volt/VAr regulation are illustrated:

1. Individual locally controlled voltage regulation and separate VAr support;
2. Centrally controlled combined Volt/VAr control; and
3. Free-standing integrated Volt/VAr control.

Specific methods of control are not indicated since at the architecture level, the specifics of *how* a particular component works internally are not of concern. Consequently no distinction is made between central and embedded dedicated controllers and agents, as these are implementation tools.

The control structure model includes specific references to microgrids and to buildings as key elements. In the buildings case, the model includes the remote control of sets of buildings in a manner that may or may not be coordinated with grid operations.

The control framework also indicates three modes of dispatch of Demand Response (DR) and Distributed Energy Resources (DER):

1. Locally, by the distribution provider;
2. From the system operator level, bypassing distribution; and
3. Via third party aggregators that may bid aggregated resources into a wholesale market and perform dispatch directly, or possibly in collaboration with a distribution utility.

Note that two of those methods involve tier bypassing (lack of coordination with the distribution company); and one, the aggregator, involves a two-level control process: one for asset dispatch, and one for participation in the market for the tertiary control loop. Figure 4.21 shows a whole grid control model, including market/control integration.

¹⁸ Receding horizon controls are a class of control systems that plan control over a time window that continually slides forward after each control time step. Model predictive control uses receding time horizons.

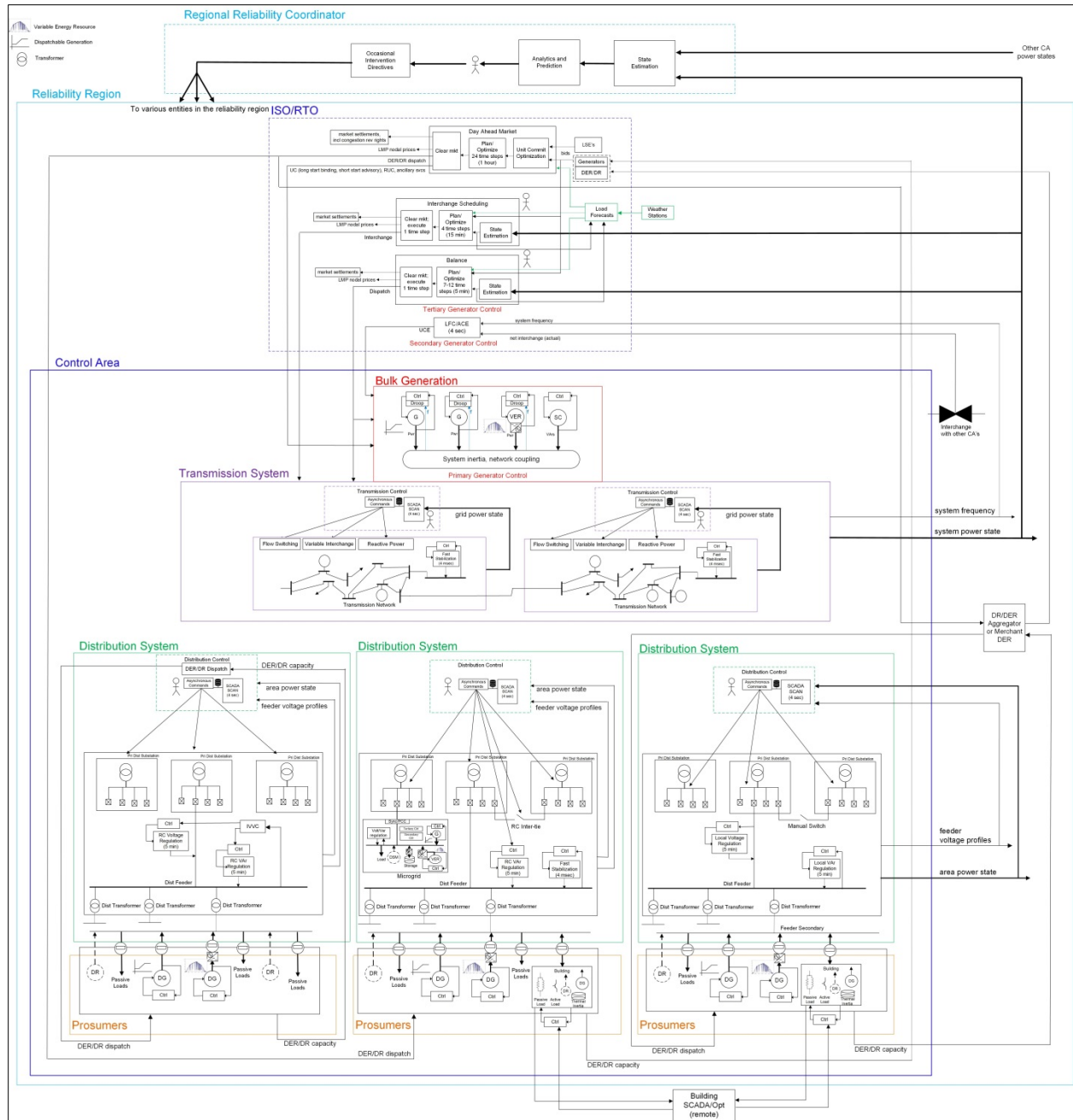


Figure 4.21. Whole Grid Control Model

Examination of the control diagram shows that distribution, while electrically connected to the rest of the system, is *not* control connected. Considering just the bulk power system, and setting DER aside momentarily, the integration of markets and system control are clear, as shown in Figure 4.22.

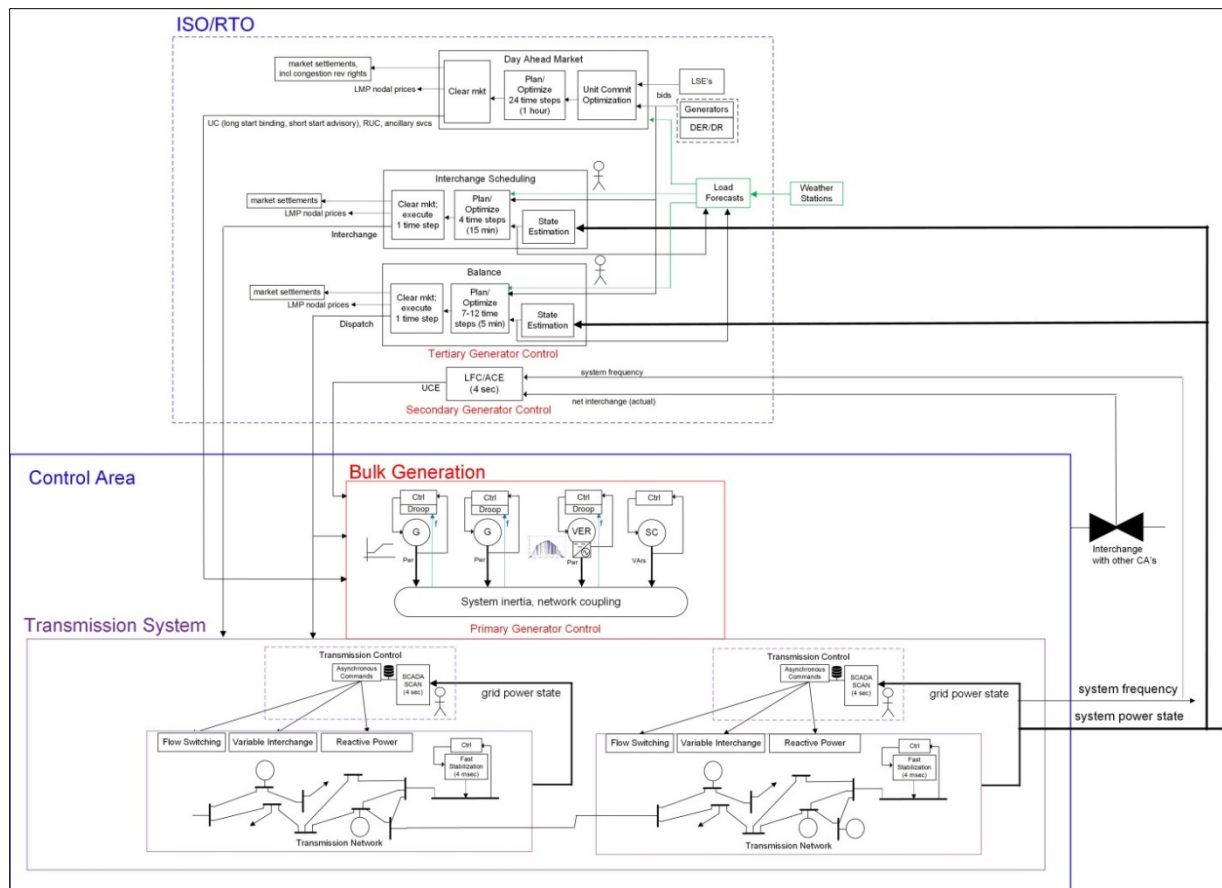


Figure 4.22. Bulk System Control/Market Integration

As the diagram indicates, the wholesale markets are not just included in—but are integral parts of—the closed loop control of the Control Area, through dispatch, balance, and load frequency control. Primary generator control relies upon local closed loops,¹⁹ droop control, system inertia, and transmission grid coupling.

Architectural Insight 11

The inclusion of real time power markets inside closed loop grid controls means that these markets could contribute to control instability. The problem will worsen with additional entities in the loop and the presence of faster dynamics and diverse sources of net load volatility.

Skeletonizing the control structure yields the coordination view, shown in Figure 4.23. The isolation of distribution operations is clearly apparent. This condition also exists in the Public

¹⁹ Closed loop control uses measurements of the controlled system, fed back into the controller, to determine incremental control corrections. Such feedback, used improperly, can cause instability (oscillation or runaway).

power/PUD/Muni/Co-op case as well, and is just as problematic. In the vertically integrated case, the functions exist within a single company or set of integrated companies, but distribution may still be isolated.

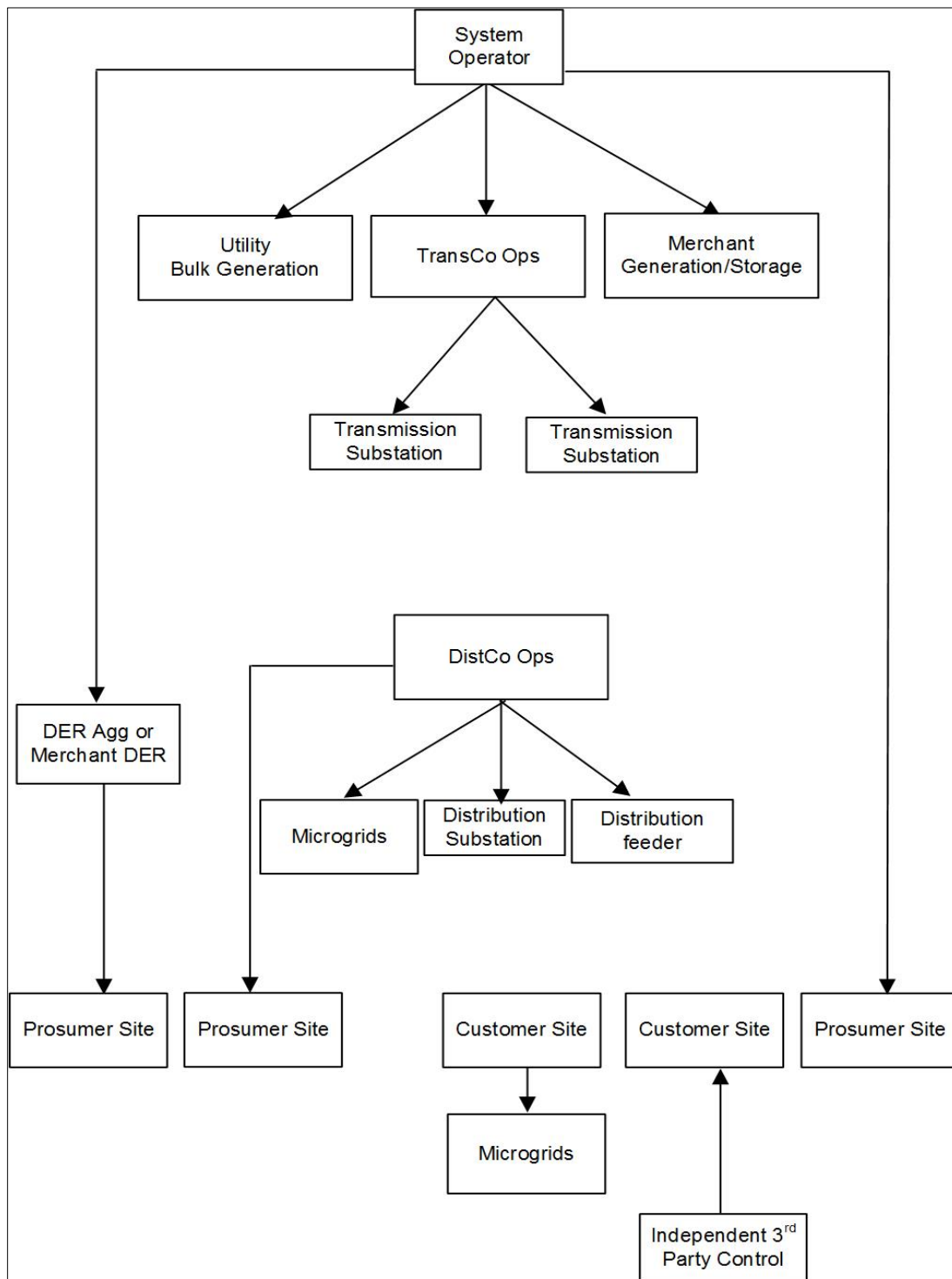


Figure 4.23. Grid Coordination Structure

Architectural Insight 12

Consider the fact that distribution control and coordination is presently not well coordinated with the rest of the grid in the light of regulatory structure, namely the Federal regulation of the bulk power system, vs. State regulation of distribution grids. Note that regulatory structure, industry structure and control/coordination structure are aligned—but this alignment is with control structures that are increasingly problematic as the grid changes due to emerging trends. Bifurcation of generation (across the transmission and distribution levels), responsive loads, dynamics associated with managing net loads vs. gross loads and the increasing impact of distribution on transmission operations suggest that new models for how reliability responsibility is allocated are needed. Such models are starting to emerge at the State level, and they may imply structural changes to reliability oversight and to markets for distributed energy resources. In addition the recent 3rd Circuit Court of Appeals ruling regarding jurisdiction over DER, and the subsequent view published by PJM conceding that DER and bulk system generation regulation should be separated add to the architectural argument for changing structure.

Policy Implications 6

The changing nature of system dynamics, implications of DER deployment at increasing scale, new technologies, and models of consumer engagement are putting pressure on regulatory boundaries that have evolved in the past century.

Current academic and industry literature suggests consideration of a new, Distribution System Operator (DSO) model, though this thinking is very new and includes a highly varied set of topics. The States of New York and California are currently engaged in regulatory proceedings that may define and establish responsibilities for what may ultimately be termed a DSO—though outcomes remain uncertain at this early juncture. A careful consideration and/or rationalization of these responsibilities might better align with system structure (bulk system vs. distribution vs. unregulated prosumers/third parties).

5.0 Selected Architectural Views for the Grid of 2030

The following material presents potential forward-looking alternatives to selected grid structures and components, driven by emerging trends and systemic issues resulting from the widening gap between existing grid structure and the desired functions and qualities of the new grid. They do not represent the only possible approaches, but they do address many of the issues reviewed in the process of this project and incorporate thinking from across many segments of the utility industry. The emerging trends, systemic issues, and forward-looking use cases that were used as input to this section are extensive and were commented on by a group of more than 40 stakeholders, including industry, university, and government participants, as part of the project process.

In addition to the need to accommodate large numbers of distributed energy resources behaving independently, injecting energy wherever they happen to be connected to the grid, creating multi-directional flows and causing flows from distribution onto the transmission system—often reversing direction from one time interval to the next—there is also a shift of operational emphasis. For the grid of 2030, it is expected it will no longer be sufficient solely to deliver energy from central stations to end-use customers, but rather, utilities should provide reliable grid operation while allowing maximum flexibility to customers to choose their sources and uses of energy.

The creation of even a **partial architecture** such as this one starts with the specification of aspirational requirements in the form of desired system (grid) qualities. These qualities were specified by DOE for the purposes of this work.

5.1 Desired Qualities List

For purpose of this exercise, DOE provided an initial list of desired qualities. These derive from customer/prosumer needs and public policy issues. The initial list was as follows:²⁰

1. Safety
2. Scalability
3. Minimum environmental footprint
4. Robustness (reliability/resilience)
5. Flexibility (extensibility, optionality, interoperability)
6. Affordability

Note that security was considered to be included in robustness. For this work, it was promoted to a full quality when the list was rationalized.

²⁰ See the Appendix 3 for definitions of the DOE Desired Qualities.

Subsequently, a property called financeability was added to the list, defined for utility assets as the combination of:

- Used and useful;
- Rate base-able; and
- Discrete and bounded.

For non-utility assets, financeability is defined as bankability, which for DER assets largely relates to two fundamental risks (using the World Bank definition):²¹

1. Construction & completion risk; and
2. Performance risk.

Lenders will want to ensure that construction costs and schedules are met and that the completed asset demonstrates specified performance before completion is achieved. Financing is largely based on a “Certainty of Revenue” associated with an asset's anticipated performance and related revenue streams performance requirements and duration. Assets with unproven, unknown performance histories and/or with uncertain revenue streams due to changing regulatory/market structures may be considered too risky to finance.

Architectural analysis suggested that some elements of the list, while very important, were not proper qualities but were in fact system properties. The final list of desired system qualities was revised to be:

1. Security
2. Safety
3. Minimum environmental footprint
4. Robustness (reliability/resilience)
5. Flexibility (extensibility and optionality)
6. Financeability
7. Affordability

Key Question 3 What makes for a proper set of System Qualities?

A good set of qualities is more than just a list of “ilities;” the items should be as nearly orthogonal (non-overlapping) as possible, should be as specific and quantifiable as possible, and should be prioritized with relative weighting factors. It is often the case that what at first may seem to be a proper quality is in fact a system property—the grid architect can help sort out the distinction.

²¹ <http://ppp.worldbank.org/public-private-partnership/financing/risk-allocation-mitigation>

5.2 Key System Properties Supporting These Qualities

For this qualities list, a key set of supporting system properties was selected by the architecture team. The properties are:

1. Observability (situational awareness)— sufficient sensing and data collection to assemble an adequate view of system behavior for control purposes
2. Controllability and dynamic stability— ability to sufficiently control grid behavior and ability to maintain stability in the presence perturbations
3. Smoothly adjustable N-way power flow— provide for adjustable and flexible power flows at all grid levels
4. Tolerance of generation/load stochasticity—reducing the dependence on being able to dispatch generation sources and accommodating net load variability
5. Convergence of T&D, natural gas, and prosumers— use of common architecture, tools, and operational methods to maximize value stream opportunities and reduce operational difficulties across these domains
6. Scalability—able to meet a range of demand levels, interaction points, geographic or time scales
7. Distributed reliability management—specific reliability management for DR/DER
8. Whole (extended) grid coordination—mechanism for cooperation across system and organizational boundaries that does not bypass tiers, organizations, or systems
9. Attack resistance/fault tolerance/self-healing— systems tolerate asset or function loss, whether through failure or attack, and act to maintain best available service despite degradation
10. Data/device/system interoperation—automated systems exchange data and messages via common and open standards without the need for custom system integration
11. Boundary deference/local optimization—control and coordination respect organization and system boundaries and provide for local optimization criteria and local constraints to be observed
12. Control federation/disaggregation—control systems combine multiple, possibly competing or conflicting objectives into uniform controls; bulk level control commands are broken down into units that can be adjusted based on local conditions, and constraints

These properties are mapped to the system qualities as part of the architecture development process. This map can be combined with the mapping of components and structures to the system properties, making a tri-partite map (see below). This map is crucial to understanding, analyzing, and optimizing the architecture.

5.3 Key Future Grid Components and Structures

Any grid architecture must deal with legacy elements; the legacy grid is not listed in detail here but is included by reference. The key forward-looking components and structures are listed below.

Key Question 4

Where do the system properties, components, and structures come from in this process?

The selection of these elements is technical in nature and is driven by the constraints, emerging trends, systemic issues, and use cases identified for the system at hand, as well as technology, regulatory, and economic information. The architecture team synthesizes the lists with input from various subject matter experts and stakeholders. Thus the selection is driven by requirements, not by desires of the architect. The architect manages the complexity and provides the framework and conceptual integrity for the architecture.

Table 5.1. Key Grid Components

Component	Description
Synchronized distribution sensing	Synchronization of measurements in any data class, but not across classes. Purpose is to provide non-skewed snapshots of grid state.
AC/DC power flow controllers/converters	Any of a variety of technologies for adjusting power flow with much more granularity than simple switching.
Bilaterally fast storage	Energy storage for which charge and discharge rates are equally fast.
Integrated planning and operations tools	Tools and methods for integrating transmission and distribution planning, gas planning, and transmission/distribution/gas operations.
Synchronized markets	Harmonized markets for electricity, natural gas and pipeline services, and other related processes and goods.
Advanced multi-mode optimizing controls	Replacement of simple PI and manual controls with controls capable of integrating multiple objectives and operating over time horizons, not just points in time.
X2grid interface and integration	Interface technologies, tools and standards for general connection of energy devices to power grids; includes integrated coordination mechanisms (see laminar coordination below).
Transactive buildings	Buildings with controls and interfaces made for connection to and coordination with grid operations (see laminar coordination below).
Meta-data management including network model management	Tools for obtaining, managing and distributing grid meta-data, including especially electric network models.
Distribution System Operators	Distributed reliability coordinators (see DSO model below).

Table 5.2. Key Grid Structures

Structure	Description
Variable mesh electric circuits	Circuits designed to provide controllable variable flow mesh capability
Microgrids	Microgrids treated as grid elements
Laminar coordination framework	Whole grid coordination framework with specifiable properties ²²
Central/distributed generation	Bifurcated generation (already emerging)
Central/distributed control	Hybrid control framework and control elements (any of several approaches should be enabled)
Business value streams	These structure always exist; it is necessary to understand them to modernize the grid
Regulatory (DSO/coordination)	Regulatory structure appropriate to the DSO models and distributed control/coordination
Industry (DSO) model	Structure for clear responsibility for distributed reliability

5.3.1 Mappings

The full mapping (components/structures to system properties; and system properties to desired system characteristics) is shown in Figure 5.1. These mappings are *crucial* architecture artifacts; they define the essential structure of the architecture itself and permit quantitative analysis and comparison.

The mapping diagrams show how architectural elements provide support to architecture properties, and how properties support desired qualities. While the diagrams only show mapping lines, in practice, each line has a detailed explanation/justification (not shown here but done for this work). In addition, each line can have a value attached to it; these values can be set to represent the degree of support flowing from left to right and become the bases for analytical evaluation of the architecture as described later.

The mapping diagrams are complex, and for a full architecture are even more complex. They can be decomposed into subsets for consumption by various stakeholders, something that involves a larger effort than this project could support. In a full scale architecture development, much front end effort would be applied to the creation and validation of these mappings with stakeholders during the construction of the architecture. That full scale process was also beyond the scope of the present project, so the mappings were created by the architecture team and commented on by various stakeholders during the project process to the extent possible given the time constraints.

²² Laminar coordination is explained more fully in Section 5.3.2.4.

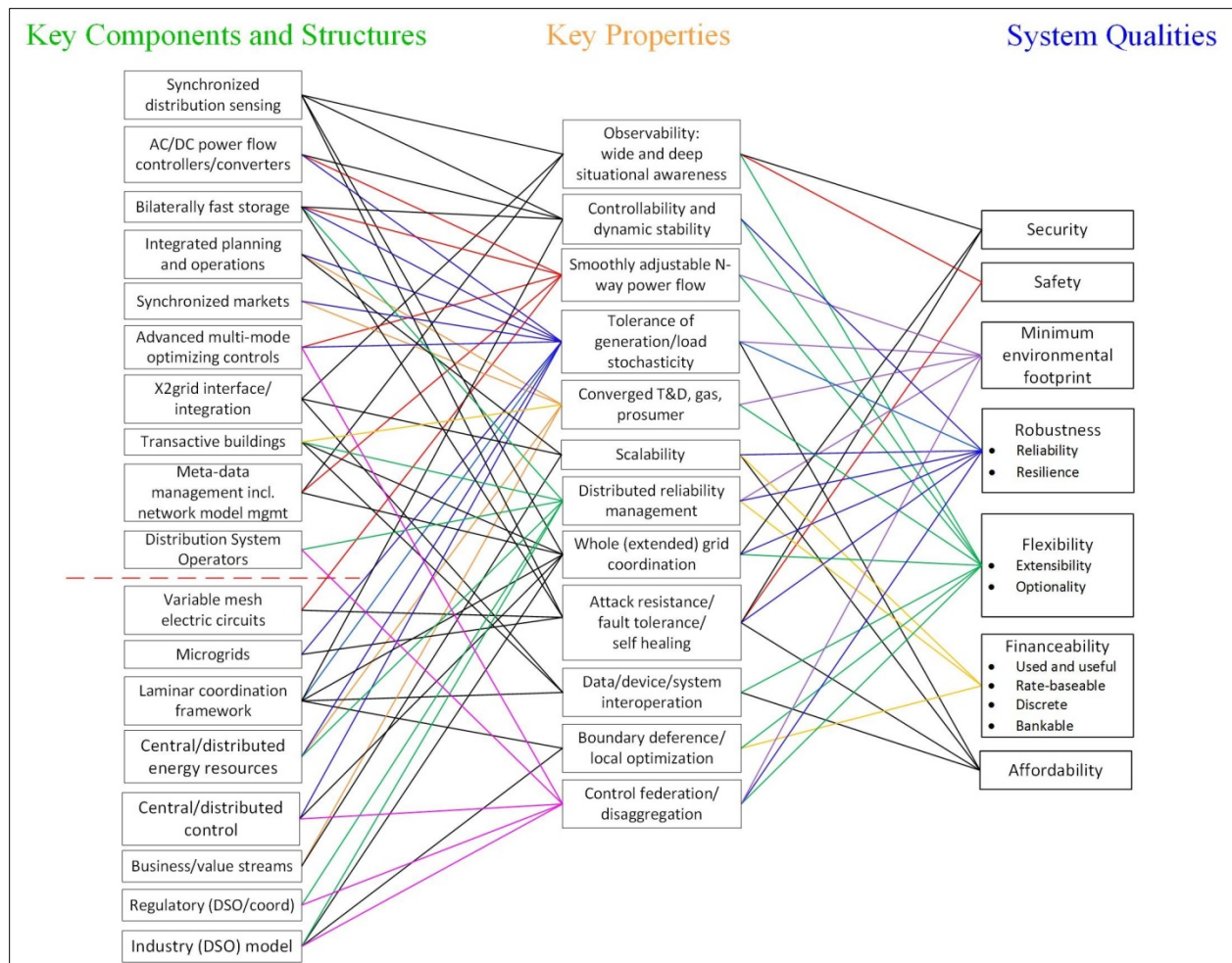


Figure 5.1. Mappings for the Partial Architecture

The lines flow from left to right and indicate support or contribution of the box on the left to the connected box on the right. The lines may be weighted with numerical values, when a basis for such values is available. In the absence of a basis, each is weighted equally. Once values are established, the diagram may be treated mathematically and both analyzed and optimized.

Key Question 5

How does the architecture impact system qualities?

The architecture mappings are the primary means by which the impact of architectural elements, singly, or in groups, or in total impact the qualities. It is vital that the mappings be well thought out and validated by stakeholders early in the architecture process. Appendix B shows some of the basics of how to convert the mappings to mathematical form for use in analysis and optimization.

Even without the detailed mathematical analysis, these diagrams can be used to understand relationships between architectural elements and system qualities. For example, tracing the effect of one component is illustrated in Figure 5.2. Un-weighted analysis of the architecture provides an easy and early indication of any element's impact on qualities like Robustness and Flexibility. Adding non-

uniform weights to the lines will alter these impacts; the method makes each assumption or consideration open and transparent. Optimizations can be formulated and solved rigorously using this approach.

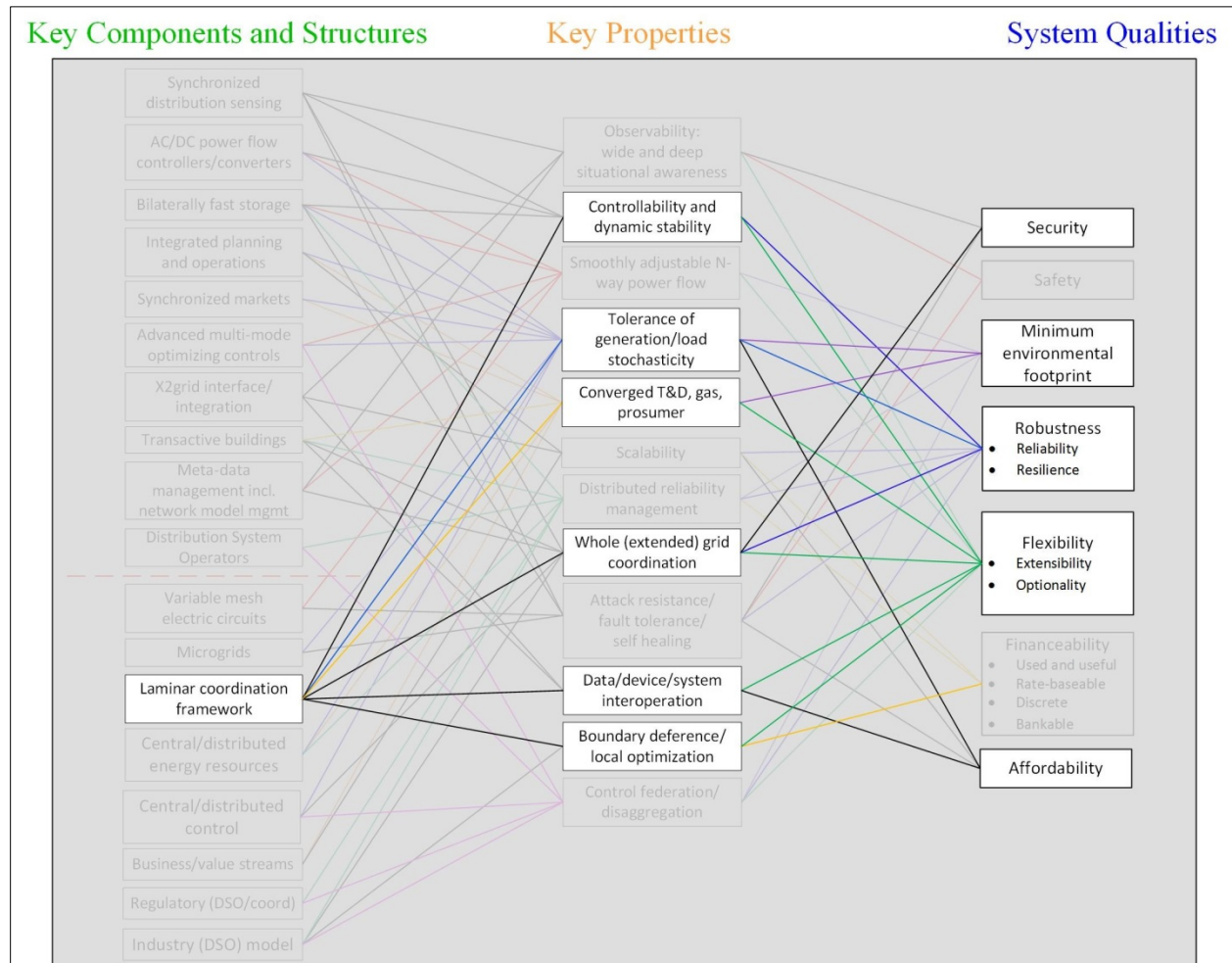


Figure 5.2. Tracing the Impact of Laminar Coordination on Qualities

Figure 5.3 illustrates tracing the impact of storage on a single quality. It is possible to do this systematically for any set of architectural elements, as well as to compare competing architectures, and to formulate and solve various architecture optimization problems, including finding best subsets of elements, based on various objectives and constraints. Weighting of the relative importance of desired system qualities is easily handled, and it is quite feasible to measure numerically how well a given architecture aligns with such priorities, as well as how much impact a given architecture has on the (prioritized) quality set.

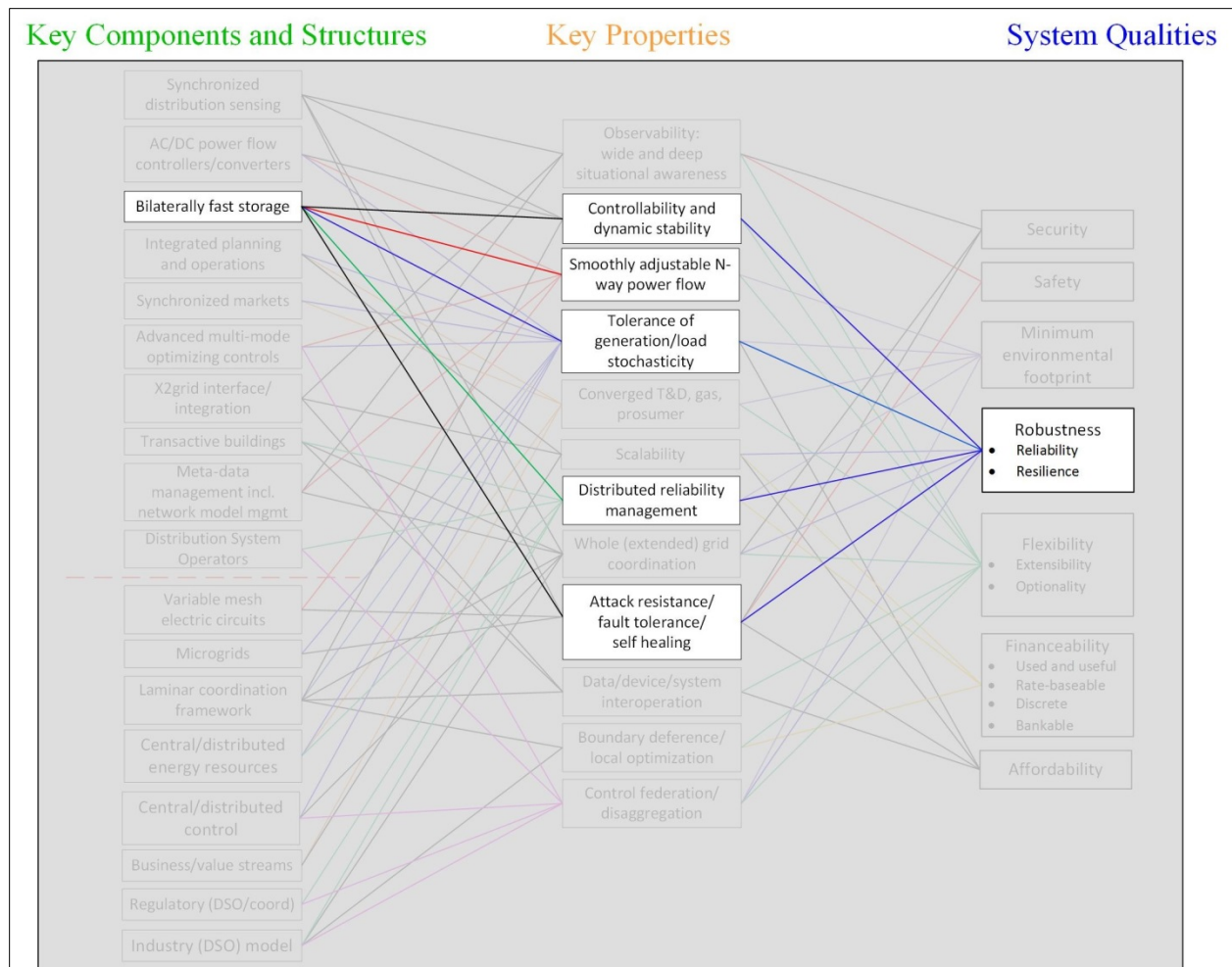


Figure 5.3. Tracing Storage Impact on Robustness

Architectural Insight 13

The ability to quantitatively analyze and optimize architectures is crucial due to the complexity of modern grids. The development and validation of the mappings is a critical early phase step in the architecture development process.

5.3.2 Selected Architectural Elements

5.3.2.1 Buildings

Buildings not only represent significant users of electricity, they also have the potential for offering services back to the grid in a transactive mode. For grid architecture purposes, buildings have several key characteristics, as detailed in the table below.

Key Question 6

What is the difference between passive load and active load?

These names have nothing to do with how the loads are controlled; they refer to inherent characteristics as elements of electric circuits. The differences, as outlined in the tables below, can be critical in determining the effectiveness of various control schemes. In general, even finer distinctions among load types than are listed here can be important for architectural purposes.

Table 5.3. Key Building Characteristics

Characteristic	Comments
Passive loads	Standard loads for HVAC/lighting, etc. Most of these behave in a manner that approximates simple impedance, although some have special characteristics in terms of inrush current, flicker, etc.
Active loads	Active loads are those using nonlinear power supplies: computers, office machines, LED lighting, entertainment systems, etc. These loads do not react to lowered line voltages in the same way as passive loads, and so concentrations of such loads can defeat the point of feeder control measures such as conservation voltage reduction.
Demand response	Given the appropriate controls and mechanisms for coordination with the grid, buildings can manage operating conditions in a variety of ways that can provide useful demand response services to the grid.
Distributed generation	Buildings may contain or support various kinds of DG, including renewables as well as dispatchable backup generation.
Thermal capacity	The thermal characteristics of buildings can be used as a form of energy storage; proper scheduling and control can transform this into energy storage that can be used in a grid services mode.
Behind the meter storage	Explicit storage capacity can be installed in buildings; with proper interface and control this can be useful as a grid service, provided the distribution grid does not block the ability of the building to put power into the grid; if so, then storage is still useful as a net load management tool and resilience measure.

Due to the significance of buildings as users of energy, the ability to marshal them for grid management purposes suggests that significant value streams should be available. From an architectural standpoint, key externally visible properties of buildings that would enable energy value streams require appropriate interfaces and controls, but most importantly, compatibility with a whole grid *coordination framework*. Without this, it takes much *ad hoc* integration work to implement any particular building to grid energy service.

Architectural Insight 14

In addition to the lack of interconnection standards, building to grid integration is hindered in some places by certain electrical structure limitations and more importantly lack of a *coordination mechanism* on the grid side that extends across the grid/building boundary.

5.3.2.2 Microgrids

Microgrids have a number of externally visible properties that are based on capabilities similar in some ways to buildings. Microgrids are electricity distribution systems containing loads and DER, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

Table 5.4. Key Microgrid Characteristics

Characteristic	Comments
Passive loads	Standard loads for HVAC/lighting, etc. Most of these behave in a manner that approximates simple impedance, although some have special characteristics in terms of inrush current, flicker, etc.
Active loads	Active loads are those using nonlinear power supplies: computers, office machines, LED lighting, entertainment systems, etc.
Demand response	Given the appropriate controls and mechanisms for coordination with the grid, microgrids can manage operating conditions in a variety of ways that can provide useful demand response services to the grid.
Distributed generation	Microgrids may contain or support various kinds of DG, including renewables as well as dispatchable backup generation.
Thermal capacity	The thermal characteristics of buildings in the microgrid can be used as a form of energy storage; proper scheduling and control can transform this into energy storage that can be used in a grid services mode.
Microgrid storage	Explicit storage capacity can be installed in microgrids; with proper interface and control this can be useful as a grid service, provided the distribution grid does not block the ability of the microgrid to put power into the grid.
Intentional islanding capability	Rather than having a simple service entrance, microgrids have a point of common coupling that is made to support disconnection from the grid, a process called islanding. Islanding raises issues such as the effect on feeder Volt/VAr regulation—when the microgrid islands, it takes over its own internal regulation, but islanding can then cause a significant change in conditions on the remainder of the feeder circuit outside of the island, if there is any. When the microgrid rejoins, it has to do so in a synchronized manner, requiring coordinated responsibility for feeder regulation.

Note that some buildings have islanding capabilities, and so may be viewed as microgrids in that case. Also, microgrids may have buildings inside of them and the ones that have their own building islanding then lead to nested microgrids. In general, this phenomenon can occur for any microgrid, especially the larger ones. In such cases, the laminar coordination framework can be continued at any necessary scale, from whole grid to specific service area to microgrid, to nested microgrid, to building, and even inside a building to individual floors or zones as needed. This multi-scale view is one of the reasons why the self-similarity/scaling aspects of the coordination framework are important, along with boundary deference and control disaggregation.

5.3.2.3 Storage

Storage applications and storage technologies have a range of requirements and external characteristics (see table above). The chart below, developed by Sandia National Laboratory, illustrates some of these characteristics.²³

Key Question 7
What is potential impact of storage on the grid?

Storage is unique in that it can be capable of taking energy or power from the grid, adding energy or power to the grid, and supplying a wide range of grid services on short (sub-second) and long (hours) time scales. It can supply a variety of services simultaneously. *The combination of fast bilateral storage, flexible grid interface mechanisms, and advanced optimizing control is a general purpose grid element as fundamental as power transformers and circuit breakers*, a conclusion recently arrived at by a group of more than thirty participants during a roundtable session at the CleanTech100 Summit in Washington, DC, October 6–7, 2014.

One of the most significant impacts of storage will be the ability to *decouple generation and load volatilities*. Since it is known that the impact of storage can be location-dependent, there is a need for new planning tools and procedures to make use of storage as a standard grid component, and to optimize storage location and size.

Table 5.5. Storage Application Characteristics

		Storage Power			Discharge Duration		
	Type	Low	High	Note	Low	High	Note
1	Electric Energy Time-shift	1 MW	500 MW	Low per ISO transaction min. (Can aggregate smaller capacity.) High = combined cycle gen.	2	8	Depends on energy price differential, storage efficiency, and storage variable operating cost.
2	Electric Supply Capacity	1 MW	500 MW	Same as above.	4	6	Peak demand hours

²³ Table adapted from “Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide,” Jim Eyer and Garth Corey, SAND2010-0815, Sandia National Laboratory, February, 2010.

		Storage Power		Note	Discharge Duration		Note
	Type	Low	High		Low	High	
3	Load Following	1 MW	500 MW	Same as above.	2	4	Assume: 1 hour of discharge duration provides approximately 2 hours of load following.
4	Area Regulation	1 MW	40 MW	Low per ISO transaction min. Max is 50% of estimated CA technical potential of 80 MW.	15 min.	30 min.	Based on demonstration of Beacon Flywheel.
5	Electric Supply Reserve Capacity	1 MW	500 MW	Low per ISO transaction min. (Can aggregate smaller capacity.) High = combined cycle gen.	1	2	Allow time for generation-based reserves to come on-line.
6	Voltage Support	1 MW	10 MW	Assume distributed deployment, to serve Voltage support needs locally.	15 min.	1	Time needed for a) system stabilization or b) orderly load shedding.
7	Transmission Support	10 MW	100 MW	Low value is for sub transmission.	2 sec.	5 sec.	Per EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications.
8	Transmission Congestion Relief	1 MW	100 MW	Low per ISO transaction min. (Can aggregate smaller capacity.) High = 20% of high capacity transmission.	3	6	Peak demand hours. Low value is for "peaky" loads, high value is for "flatter" load profiles.
9.1	T&D Upgrade Deferral 50th percentile	250 kW	5 MW	Low = smallest likely, High = high end for distribution & subtransmission.	3	6	Same as Above
9.2	T&D Upgrade Deferral 90th percentile	250 kW	2 MW	Same as above.	3	6	Same as Above

		Storage Power			Discharge Duration		
	Type	Low	High	Note	Low	High	Note
10	Substation On-site Power	1.5 kW	5 kW	Per EPRI/DOE Substation Battery Survey.	8	16	Per EPRI/DOE Substation Battery Survey.
11	Time-of-use Energy Cost Management	1 kW	1 MW	Residential to medium sized commercial/industrial users.	4	6	Peak demand hours.
12	Demand Charge Management	50 kW	10 MW	Small commercial to large commercial/industrial users.	5	11	Maximum daily demand charge hours, per utility tariff.
13	Electric Service Reliability	0.2 kW	10 MW	Low = Under desk UPS. High = facility-wide for commercial/industrial users.	5 min.	1	Time needed for a) shorter duration outages or b) orderly load shutdown.
14	Electric Service Power Quality	0.2 kW	10 MW	Same as above.	10 sec.	1 min.	Time needed for events ride through depends on the type of PQ challenges addressed.
15	Renewables Energy Time-shift	1 kW	500 MW	Low = small residential PV. High = "bulk" renewable energy fueled generation.	3	5	Depends on energy cost/price differential and storage efficiency and variable operating cost.
16	Renewables Capacity Firming	1 kW	500 MW	Same as above.	2	4	Low & high values for Renewable Gen./Peak Load correlation (>6 hours) of 85% & 50%.
17.1	Wind Generation Grid Integration, Short Duration	0.2 kW	500 MW	Low = small residential turbine. High = large wind farm boundary.	10 sec.	15 min.	For a) Power Quality (depends on type of challenge addressed) and b) Wind Intermittency.
17.2	Wind Generation Grid Integration, Long Duration	0.2 kW	500 MW	Same as above.	1	6	Backup, Time-Shift, Congestion Relief.

Discharge Durations are Hours unless indicated otherwise. Min. = minutes. Sec. = Seconds.

Furthermore, it has been shown that some forms of storage can be controlled in such a way as to provide multiple value streams simultaneously.²⁴ The keys to this and other capabilities are several elements:

²⁴ Di Wu, Chunlian Jin, Patrick Balducci, and Michael Kintner-Meyer, "An Energy Storage Assessment: Using Optimal Control Strategies to Capture Multiple Services," available from Pacific Northwest National Laboratory.

- Fast bi-lateral storage— the storage unit must be symmetrical in its charge and discharge characteristics and ramping must be fast
- Power interface—the connection to the grid must provide fast controllability of output voltage, real power and reactive power
- Advanced control—the storage control must be capable of fusing multiple objective and constraints into a single control solution

Given these capabilities, not only can storage offer multiple value streams, it can do so while sharing the cost across those streams, instead of requiring one storage unit for application A, and another for application B, etc. Other potential applications include energy park-and-loan, electric “line packing,” and warehouse/inventory for energy transactions.

With sufficiently fast storage and interface technologies, storage may be applied to the problem of *augmenting* grid inertia, thus making up for inertia being lost due to changes in the generation mix. Virtual inertia is a concept whereby storage interacts with the grid in a specific manner dictated by the physics of rotational momentum, namely the flow to/from the storage unit must be proportional to the rate of change of system frequency.²⁵ This is not a frequency regulation issue; it is a small signal stability and primary generator control issue.

5.3.2.4 Whole Grid Coordination (Laminar Coordination Framework)

Coordination is the means by which distributed control elements are made to cooperate to solve a common problem (in this case, grid control). The previous discussion has shown that existing whole grid coordination has gaps. The existing coordination framework for the grid is uneven in coverage and does not have a rigorous foundation, so its properties are essentially unknown except through empirical experience. Some of its elements work well, but as the grid experiences penetration of new technologies and capabilities, there is a kind of drifting separation that is enlarging the gap between grid control/coordination and grid behavior and capabilities.

This drift is being addressed in a bottom-up fashion through the development of various control schemes.²⁶ These include so-called “flat grid” approaches involving agents, cellular automata/“fractal” layering, multi-scale two layer control, hierarchical control, layered decomposition, Transactive Energy, and many others. The industry by and large has come to the conclusion that a transition from centralized control to some form of hybrid central/distributed control is necessary for grid modernization, but has not and probably will not converge on a single approach. While it is not the purpose or role of grid architecture to specify a particular control technique, it is appropriate to consider architecture changes that could resolve structural issues that address limitations and gaps in control framework, and where possible, free up constraints so that any necessary control technique is not blocked or hampered unnecessarily.

Some key properties of a new coordination framework include:

- Ability to fully coordinate grid elements with no tier bypassing or isolated entities

²⁵ Miguel Torres and Luis A. C. Lopes, “Virtual Synchronous Generator: A Control Strategy to Improve Dynamic Frequency Control in Autonomous Power Systems”, Energy and Power Engineering, April 2013

²⁶ See Appendix F for some representative samples of alternative control/coordination approaches.

- Boundary deference and enablement of “local selfish optimization”—the ability of systems and organization to participate in a manner consistent with local objectives and constraints
- Support control federation so that competing or conflicting control objectives can be resolved in a non-ambiguous manner
- Scalability of coordination data traffic
- Properties derive from a rigorous basis instead of *ad hoc* bottom-up emergent behavior

Recent work on the theory of network architectures²⁷ has provided a basis for deriving a coordination structure. This work provides a recursive decomposition approach that *implies* a structure for coordination. The resultant structure can be used for coordination on any scale, and can even be used to formulate control problems directly if desired. See Appendix 3 for more information on the formal basis for this structure.

The significance of this approach to coordination is that it supports not just multiple approaches to grid control, *but multiple simultaneous approaches*. So for example, it is possible to mix classical centralized control with Transactive Energy methods, alongside multi-agent distributed control and hierarchical control, all in the same system with a means to coordinate across these control methods. Therefore, approaches that use modular cells communication with neighbors, or flat arrangements using roving multi-agent systems, or multi-scale are all envisioned here. The key is that when a coordination mechanism is needed, it should be available in a form that has predictable properties. This flexibility aids the affordability aspect of modern grids by reducing the likelihood of stranding investments in control approaches.

Architectural Insight 15

The key principle for a mix of centralized and distributed control that provides properties such as boundary deference, control federation and disaggregation, and scalability is:

Local Optimization Inside Global Coordination

Note that coordination is not control, although goal decomposition coordination mechanisms can be used to solve control problems if desired.

The structure derived from the cited advances in network architecture is comprised of a recursive layering of optimization nodes, with both hub-and-spoke inter-layer communications and peer-to-peer communications per layer. Coordination is based on the joint solution of decomposed optimization problems by the entire set of nodes, resulting in the necessary coordination signals for each control element. The mathematical basis suggests a network of coordination nodes, where each node solves some

²⁷ Mung Chiang, Steven Low, et al,” Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures”, Proceedings of the IEEE, Vol. 95, No. 1, January 2007.

aspect of a larger optimization problem, communicating with the nodes logically above and below it, and possibly with its neighboring peers. The basic coordination framework structure is shown in Figure 5.4.

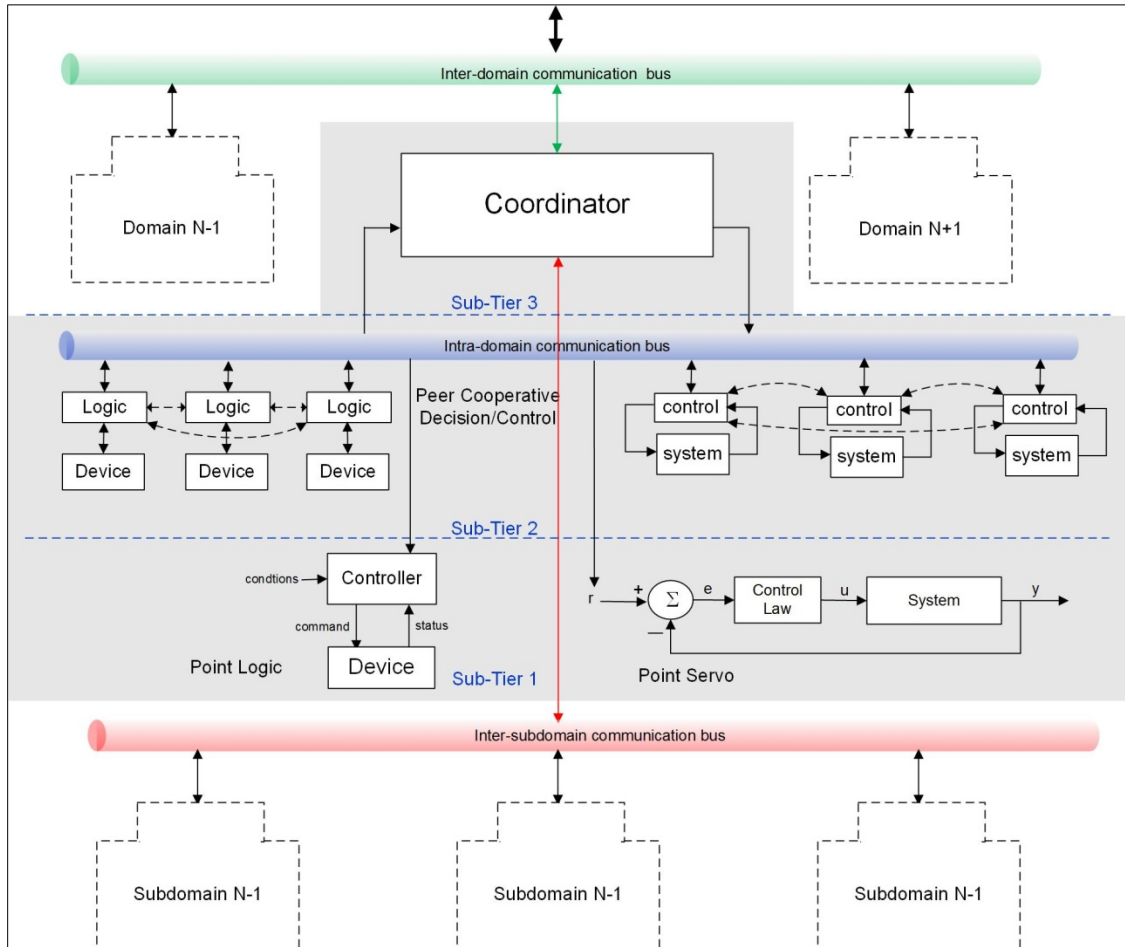


Figure 5.4. Coordination Node and Domain

Each node has a local domain that can include as many or as few devices and subsystems as necessary. In other words, a domain can be a single device, a building or microgrid, a distribution feeder, a substation service area, a distribution service area, even a whole control area. Multiple domains at the same level can implement the modular microgrid or cellular automata approaches to grid design, with neighbor to neighbor communication as well as a scaling coordination mechanism if needed. The approach inherently supports multiple scales, as many as needed. Note that by assigning roles, this approach accommodates many of the common approaches to distributed grid control and in fact can coordinate multiple co-existing approaches simultaneously. At each level and node, local optimization criteria and constraints can be applied, providing local selfish optimization in a coordinated framework, and since new decompositions can be defined as needed, any system, organizational or regulatory boundary can be accommodated. The model inherently accommodates a distribution of time scales that matches the distribution of time scales inherent in existing grid structure. The essential structure is shown in Figure 5.5.

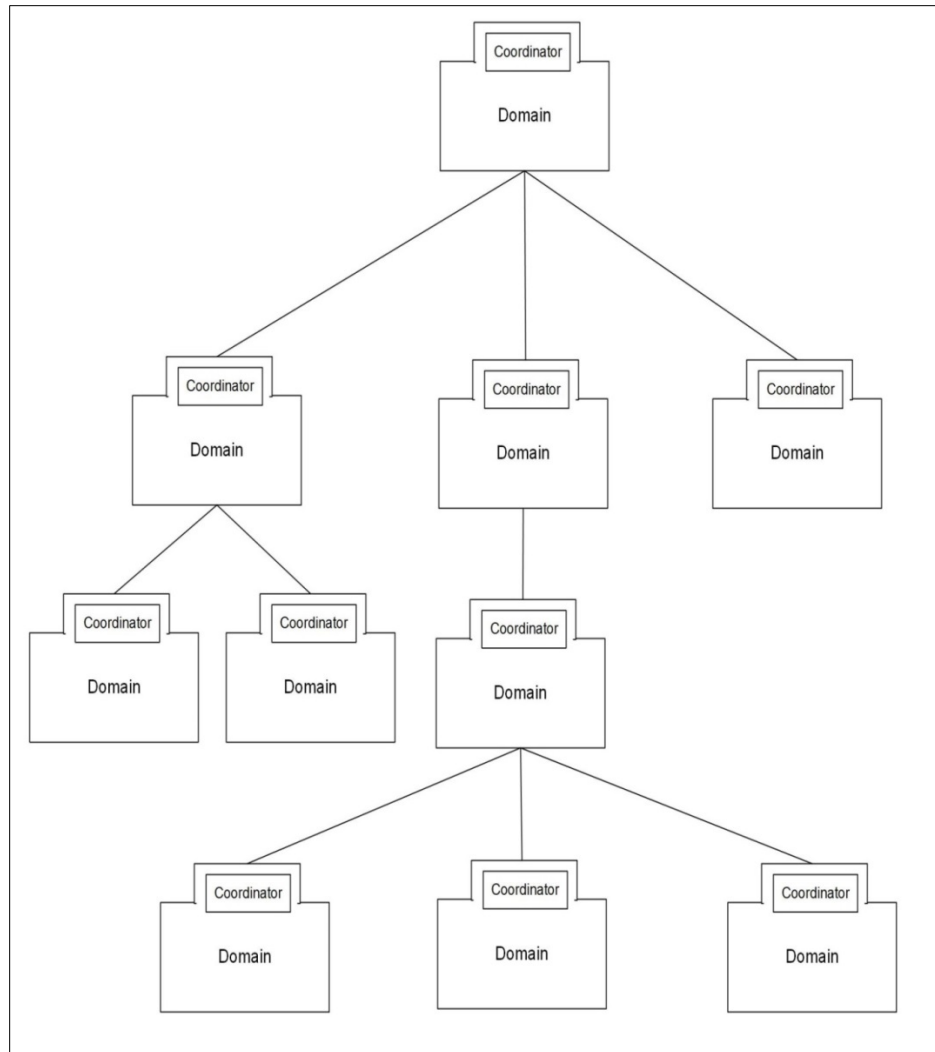


Figure 5.5. Essential Coordination Structure

Key Question 8

How Does Laminar Coordination Provide Local Optimization within Global Coordination?

Laminar Coordination uses a mathematical method to align the work being done at each level. Essentially all of the nodes cooperate to solve a common optimization problem, which results in the necessary coordination signals. Locally each process can carry out optimization using local goals and constraints within the coordination framework. See Appendix D for more detail.

Such a structure can be mapped onto any version of both grid and industry structure, which is a very powerful property, that leads to both boundary deference and scalability. A simple illustration of mapping this structure to standard grid infrastructure is shown in the figure below. The diagram shows mapping of the coordination network to the grid, as well as key data flows for coordination and peer-to-peer interaction. Note that the coordination nodes may use many different approaches to solving the common optimization problem: they may perform traditional optimization, act as transactive nodes that use a market-like mechanism for optimization, or employ advanced techniques to solve aspects of grid

control problems so as to provide disaggregated dispatch and set point values to local subsystems and device controls. The coordination mechanism does not have to be used in all instances, but the lack of such a mechanism is a structural impediment to proper grid operation involving new energy value streams. Grid and building mapping is illustrated in Figure 5.6.

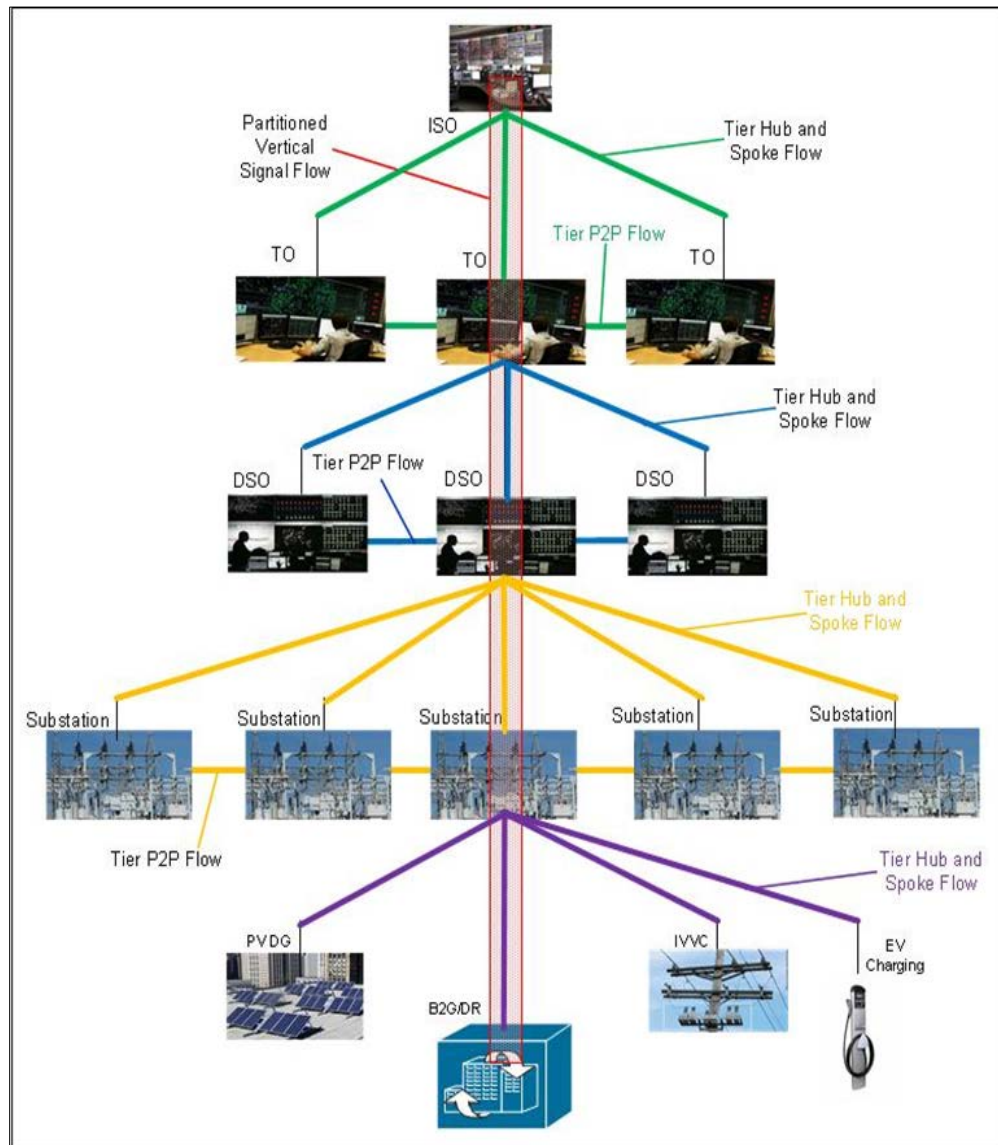


Figure 5.6. Mapping Laminar Coordination to Grid and Buildings

5.3.2.5 Industry (DSO) Model and Distribution System Operators

The DSO concept is in its early conceptualization stages and will likely evolve considerably over time. The purpose of the discussion here is to show that regardless of the details of DSO responsibility, the concept has the potential to untangle an emerging issue related to distributed reliability responsibility, and can be done in a way consistent with another structural issue, that of whole grid coordination.

Existing distribution companies have state-legislated responsibility for reliability at the distribution level, defined in 20th Century terms as relating to outages and outage management, Volt/VAr regulation on feeder circuits, and power quality (harmonics, flicker, etc.). The rise of DER, microgrids, and transactive/responsive loads is changing the nature of reliability at the distribution level. In cases where system operators dispatch DER directly, or third party aggregators do so, whether it is prosumer-owned DER or merchant DER, the issue of maintaining proper operation of the distribution grid has not only become more complicated, but involves a mix of players with no clear cut responsibility for managing impacts on distribution grids and grid operation.

Further, DER can serve to mask gross load, so that system operators see only net load, which can change drastically and quickly. Given that residential DR is not firm dispatchable and that the dynamics of both residential DR and building energy services to the grid are not as fast as some of the impacts of certain forms of DG, having conflicting control objectives and multiple responsible or at least privileged parties involved has led to a reconsideration of roles and responsibilities for distribution. Revising roles in the management of distributed reliability is an emerging concept that has structural implications. This grid architecture element draws upon the emerging thinking on distributed reliability.²⁸

Key Question 9

Why shouldn't DER be dispatched by Independent System Operators, since they have system balancing and reliability responsibilities and also operate wholesale markets?

The Independent System Operator approach has led to several problems that have led to the industry seeking other arrangements. First, letting the Independent System Operator handle DER causes a bypassing of the Distribution Provider, which introduces ambiguity in the responsibility for distribution reliability, compromising the ability of the Distribution Provider to manage its assets and operations. Second, as the number of devices that could participate in the markets and in grid operations grows, a scaling problem arises in terms of communications when the number of participants expands from dozens to tens of millions or beyond. The DSO model provides a structural mechanism for bounding this scaling. In addition, the solutions for the control mechanism of which the markets are part grow exponentially in complexity and computational requirements, as well as adding latency to the control loops which contain the markets. Finally, not all of the country is serviced by Independent System Operators.

Figure 5.7 below illustrates an industry structure that employs the concept of the DSO as manager of distributed reliability and interface to the bulk power system.

²⁸ Lorenzo Kristov and Paul De Martini, "21st Century Electric Distribution System Operations," CalTech Resnick Institute, 2014, available online: <http://resnick.caltech.edu/docs/21st.pdf>

Disaggregated U.S. Utility Industry Operational Structure (DSO Model)

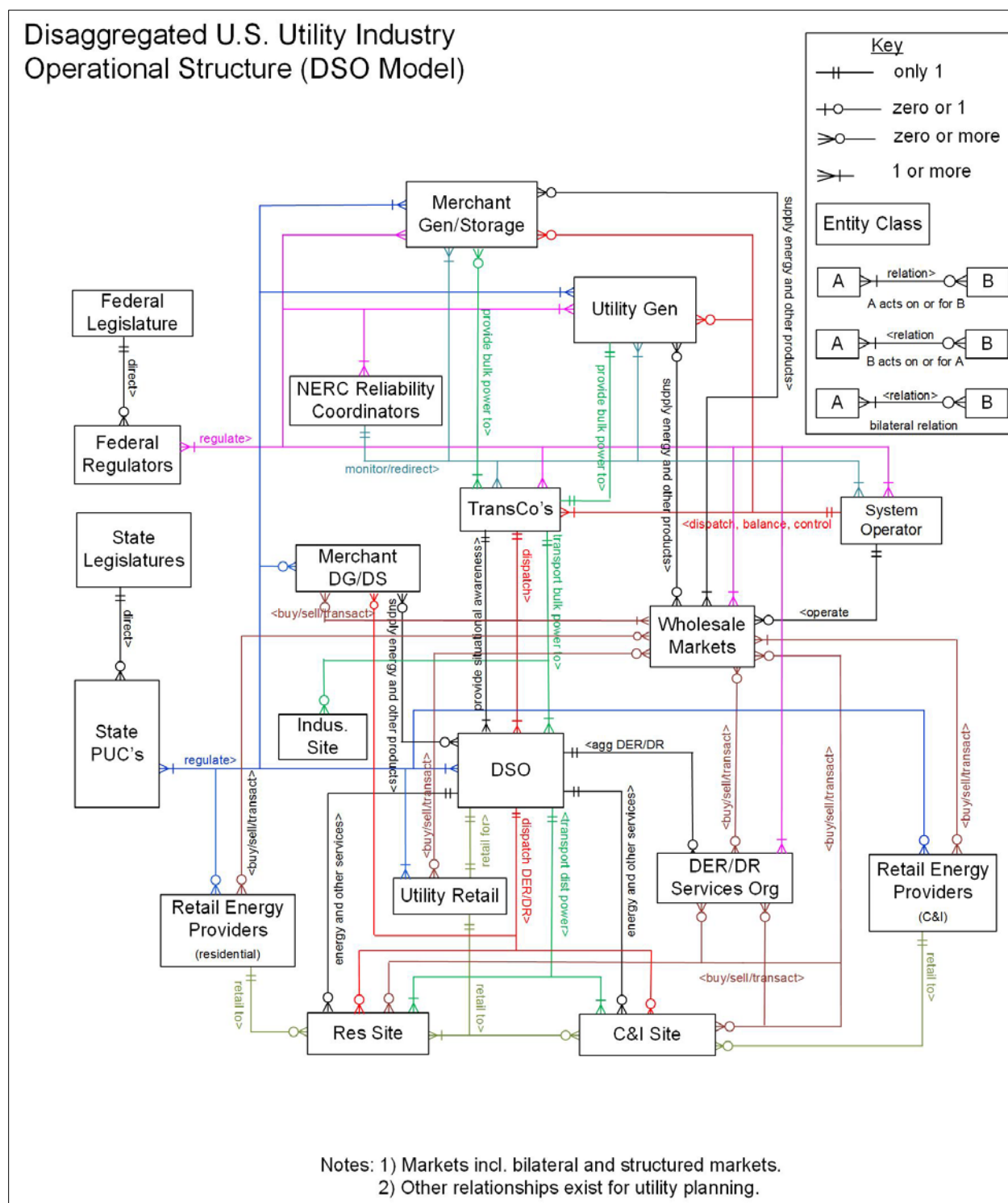


Figure 5.7. Possible DSO Industry Structure

This model addresses the disconnect seen in the existing models for grid control and coordination. To see this, remove all but the coordination and market relationships lines from the DSO model, as shown in Figure 5.8.

Disaggregated U.S. Utility Industry Operational Structure (DSO Model)

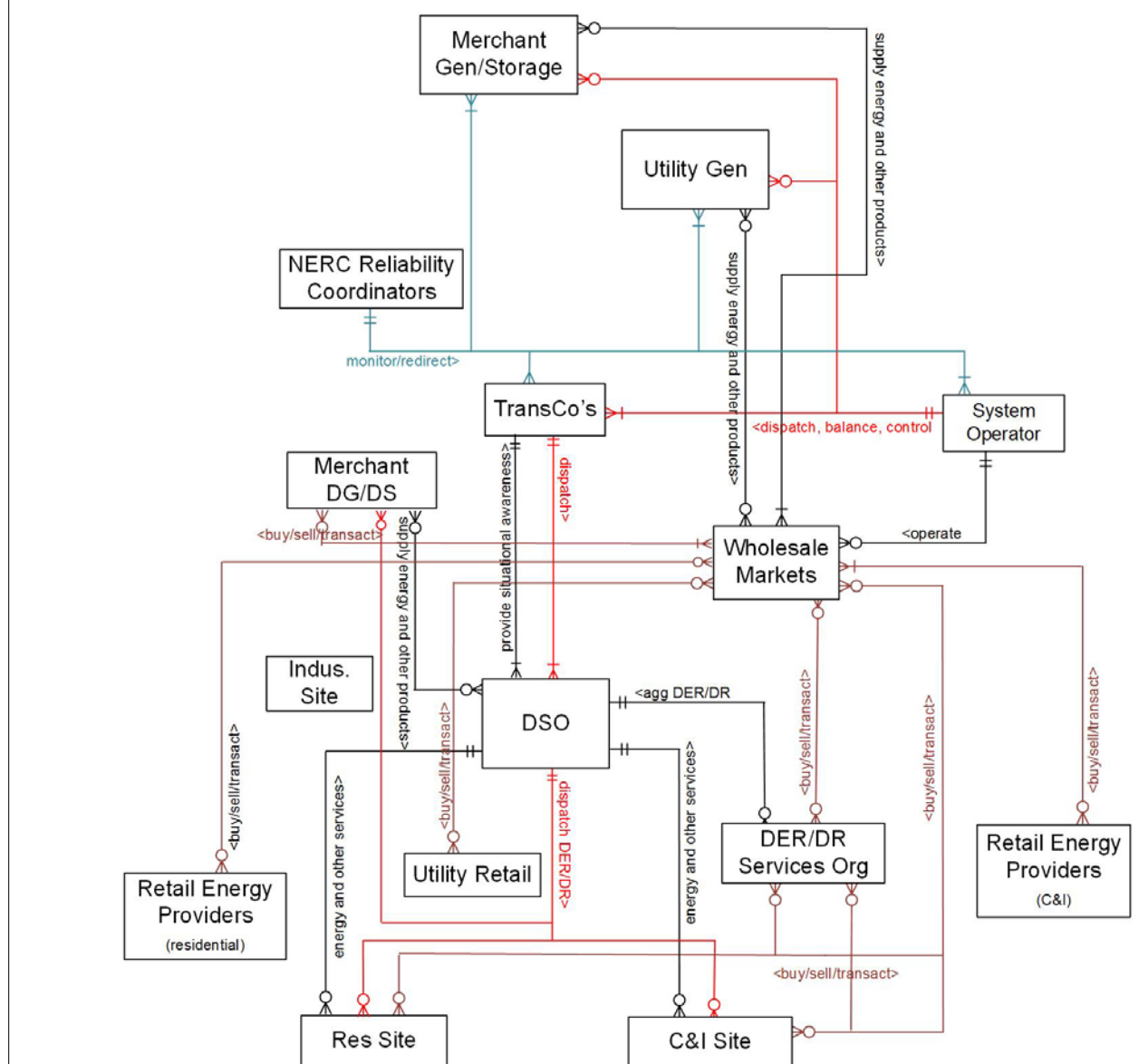


Figure 5.8. Uncluttered DSO Model

Rearranging box locations without changing essential topology yields a clearer picture of resulting coordination structure, shown in Figure 5.9.

Disaggregated U.S. Utility Industry Operational Structure (DSO Model)

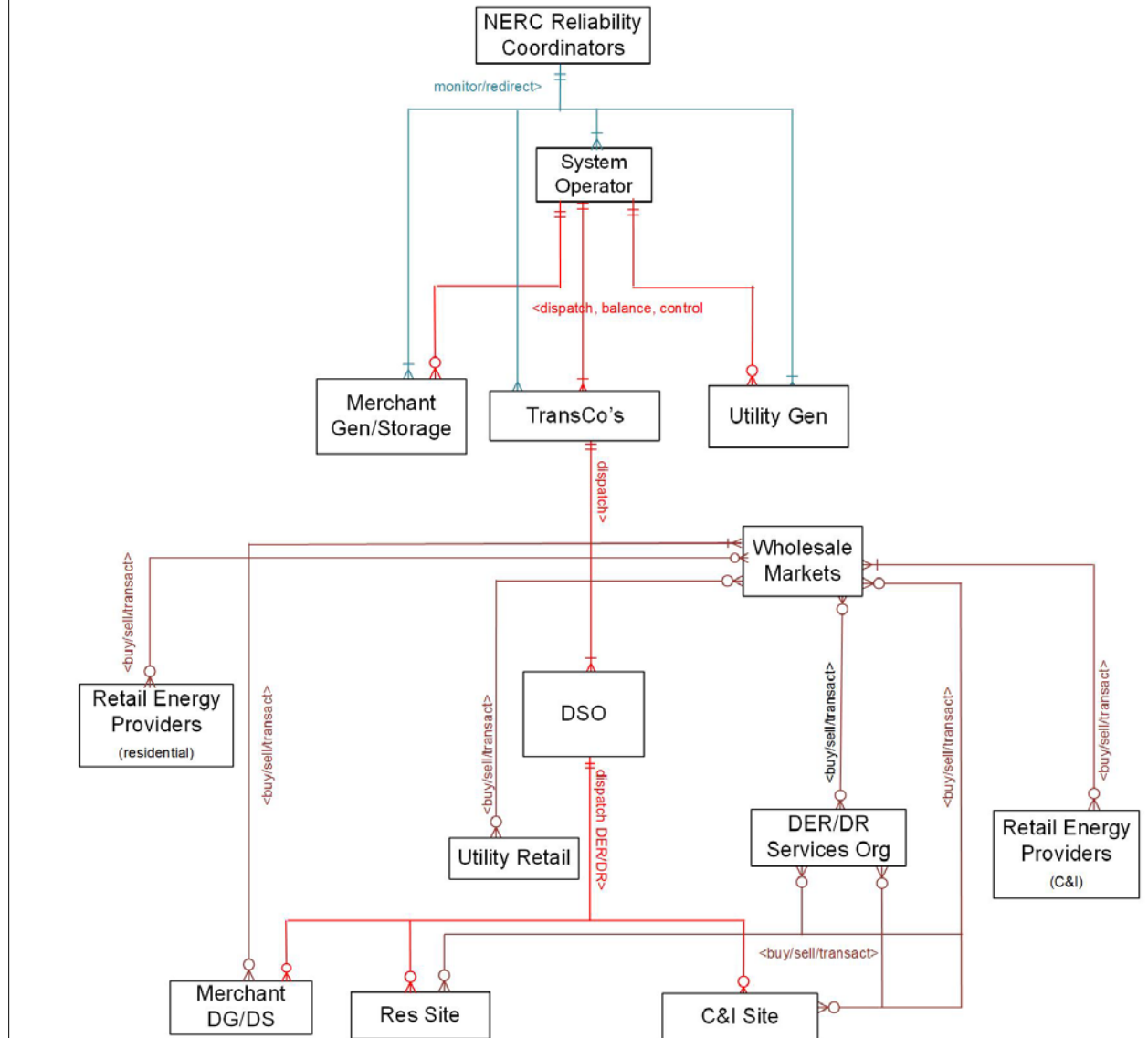


Figure 5.9. Clarified DSO Structure

Using the new industry structure as a starting point, a new whole grid skeleton coordination framework that incorporates the industry structure is shown in Figure 5.10.

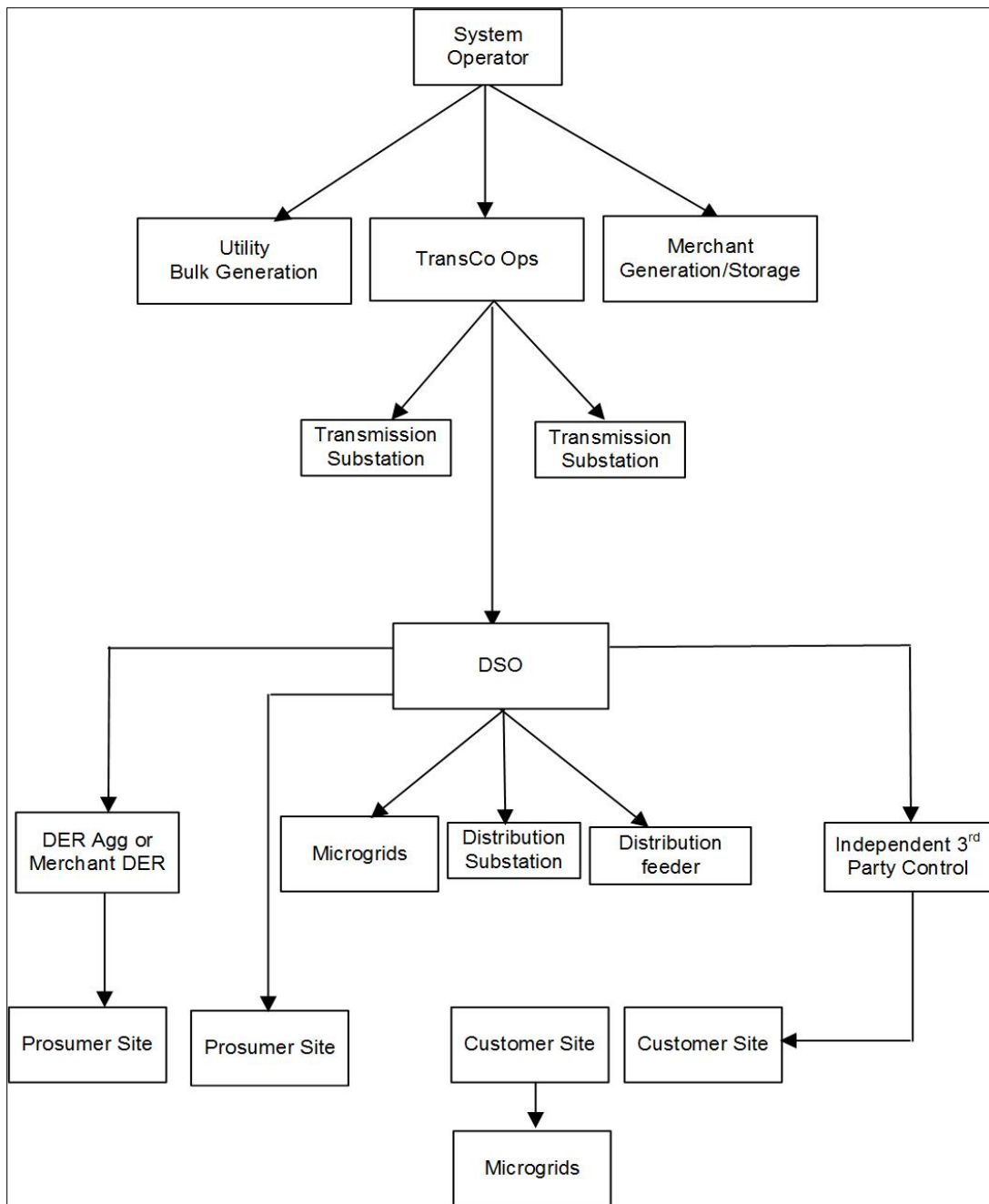


Figure 5.10. DSO-Based Coordination Structure

Note that this structure is entirely compatible with the laminar coordination framework described above. The corresponding DSO value stream framework is shown in Figure 5.10.

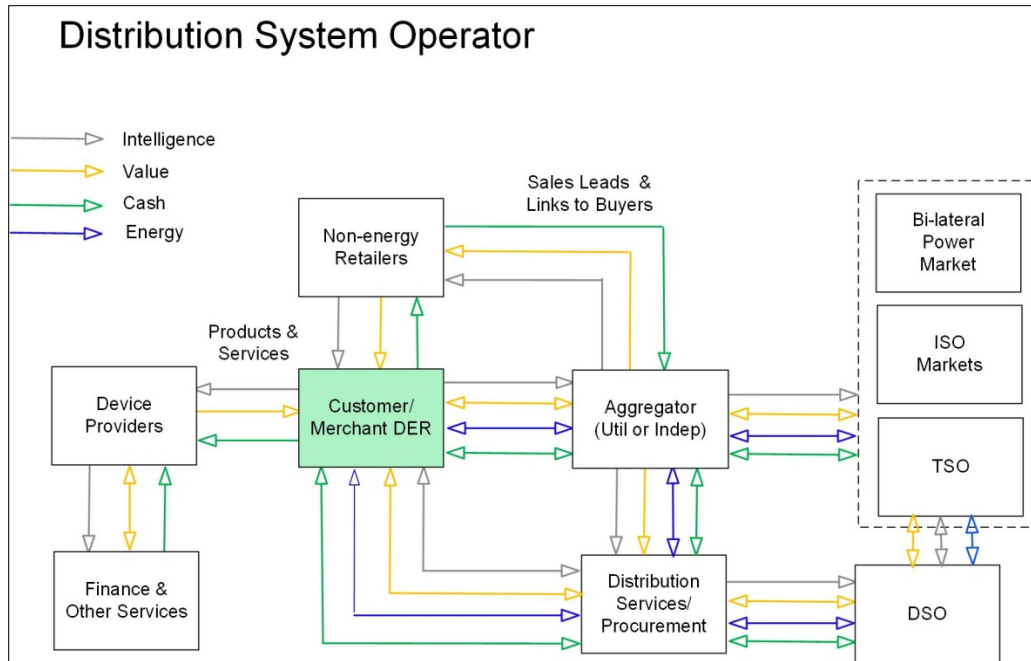


Figure 5.11. DSO Value Stream Structure

Architectural Insight 16

Note that the DSO-based industry structure, while motivated by the need to clarify and simplify responsibility for distributed reliability, arrives at a result entirely consonant with the laminar coordination structure. Since the laminar structure was motivated by the need for whole grid coordination with a rigorous basis for predicting properties such as scalability, it is reasonable to expect that the DSO model can share those properties that derive from such

5.3.2.6 Flexible Distribution Circuits

Existing distribution circuit structure imposes severe constraints on power flow, and contains multiple sources of electric coupling that hamper new functionality through undesired interactions. In order to unlock the potential of new distribution level technologies and to enable distribution companies to offer new services, changing the structure of distribution circuits from radial trees to partially meshed circuits with adjustable power flow control is necessary. Precedent for this exists in the South Korean power grid. KEPCO has created a highly interconnected distribution grid, with cross-feeder interconnections as often as every kilometer in densely populated areas. Automated controls re-route power flows across feeder sections to maintain feeder balance and provide high reliability.

Here the partial mesh circuit structure is aided by replacing selected inter-tie and flow switches with adjustable flow controllers. In addition, provision is made for distribution level storage (community storage and primary substation storage) and for primary substation distributed generation. The components are described in the table below.

Table 5.6. Flexible Partial Mesh Circuit Elements

Component	Description/Properties
Power flow controllers and inverters	Devices that adjust the flow or real and/or reactive power in a continuous way, as opposed to simple switching.
Distribution level storage	Energy storage connected at the distribution level. It may be located in substations, in community level installations, in a microgrid, or behind the meter in a building, residence, or plug-in electric vehicle.
Advanced optimizing control and advanced protection systems	Controls capable of solving multi-objective, multi-constraint problems in real time, preferably in a manner consistent with the laminar coordination framework.
Synchronized measurement at the distribution level	Improved observability via fast synchronized power state measurements; this includes but is not limited to distribution phasor measurement units (dPMU's); synchronization does not have to be the same across different data classes (i.e. AMI data does not have to synchronize with dPMU data).
Fast feeder stabilization	High speed devices capable of stabilizing feeder voltage or reactive power flow, with response times as fast as 1/4 cycle (about 4 msec).
Primary substation generation	Generation attached to or located in primary distribution substations. It may be large enough to supply bulk power to the substation service area, or may be only enough to supply grid ancillary services.
Transactive buildings	Buildings capable of supplying services to electric grids, preferable in a manner consistent with the laminar coordination framework.
Merchant DER	Distributed Energy Resources owned/operated by merchant companies, even if the DER resources reside at premises whose owner does not own the DER.
Prosumer DER	DER owned/operated by a premises owner.

Figure 5.12 illustrates the new distribution electric structure. The diagram depicts power flow control at several points, but is not intended to specify that every substation be connected to every other this way. Due to the wide variations in distribution system implementations; it must be left to the distribution company to best determine how to engineer specific partial meshing, flow control and advanced protection. Similarly, the utility would determine the best locations for flow controllers intended to break specific constraints imposed by traditional distribution circuits.

Key Question 10

Is power electronics the only available tool to finely adjust AC power flow?

No, there are several means to adjust power flows in AC power systems, including phase shift transformers, variable frequency transformers, and power electronics. Power electronics gets much attention as an edge connection tool, in the form of inverters for solar PV and battery storage for example, but can be used internally in the grid for power flow control as well.

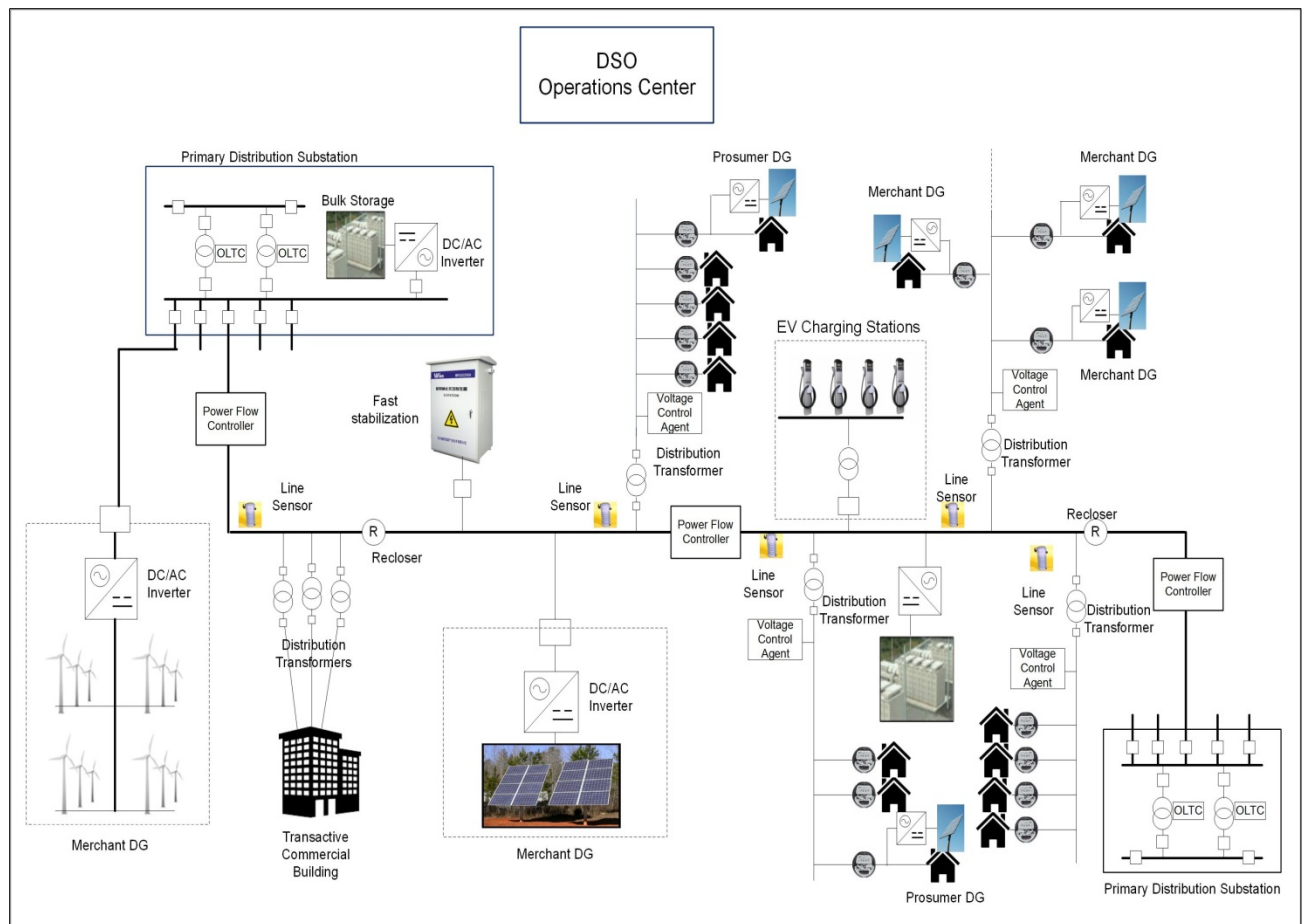


Figure 5.12. Flexible Distribution Grid Structure Illustration

See the case study below for more description of the use of this structure.

Architectural Insight 17

Key limiting issues on distribution are lack of adequate observability, lack of advanced protection systems to address multi-directional power flow, and lack distributed control and coordination systems.

Distribution grids suffer from poor observability (lack of sensing) and very little effort has gone into developing observability strategies and tools for design of distribution grid sensor networks. Advanced distribution grids must have excellent observability, so these issues must be addressed.

As DER penetration increases, adjustable flow control can be used to provide flexibility in electric circuit operation. It can also be used to cut or limit the effect of some kinds of constraints that exist in present circuits, such as unwanted cross feeder flows or unscheduled flows to the transmission system.

Partial meshing provides more paths for power flow (with flow controllers directing the “traffic”) so that it becomes possible to make more effective use of DER, meaning that cost effectiveness of such assets is enhanced two ways: better sharing of the assets, and enablement of new value streams and innovations.

6.0 Case Studies

6.1 Storage as System Inertia Augmentation in a Multi-Services Environment

Degradation of system inertia has been identified as an emerging grid control issue, linked to the emergence of wind and solar as energy sources. The impact of such degradation on power system stability is now understood to be both locational and time-varying.²⁹ Various possibilities exist for augmentation of lost system inertia—one of those is the use of storage with appropriate control. Such an arrangement is illustrated in Figure 6.1.

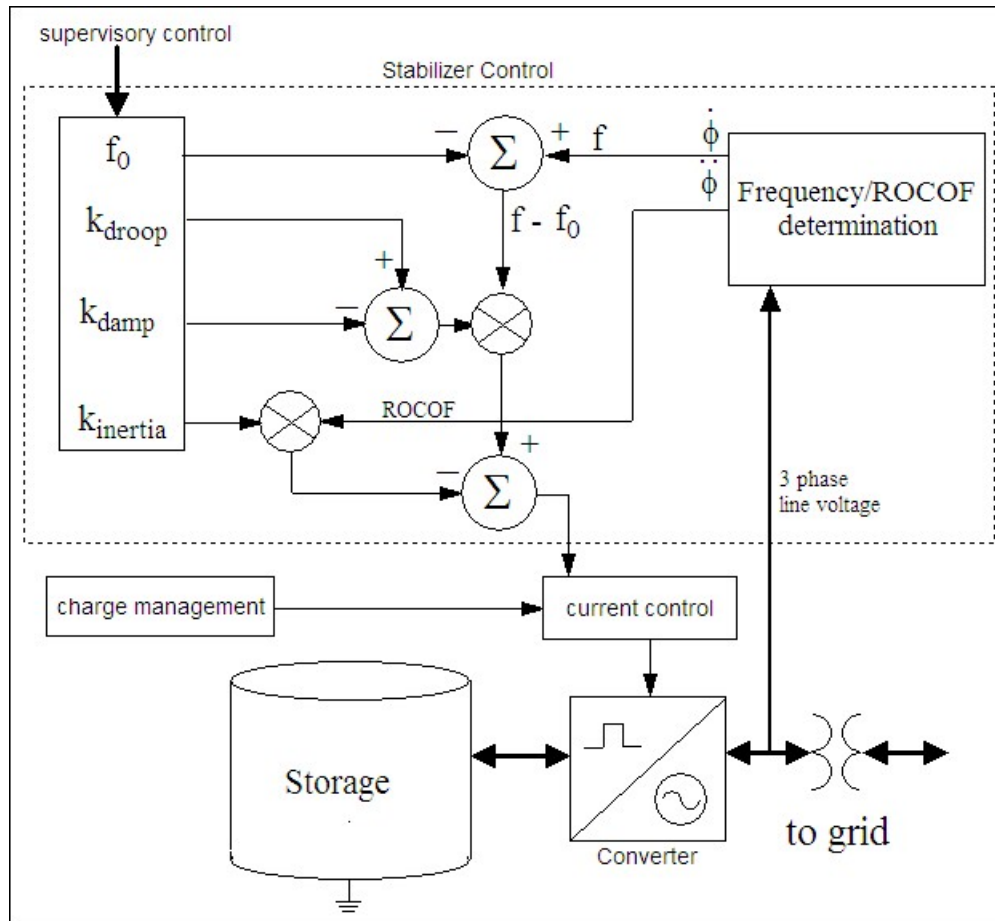


Figure 6.1. Combined Grid Damping and Virtual Inertia from Storage

A set of value streams associated with storage has been discussed earlier and virtual inertia was mentioned briefly. Now assume that grid connected storage could, in addition to its other functions, simultaneously provide some amount of augmentation of system inertia. This would be done by using some fast bi-lateral form of storage since the inertia process requires both supply and absorption of energy

²⁹ Andreas Ulbig, et al, "Impact of Low Rotational Inertia on Power System Stability and Operation", accepted for IFAC World Congress 2014, Capetown South Africa, April 2014. Available online: <http://arxiv.org/pdf/1312.6435.pdf>

on short time frames. This is due to the fact that the inertia function must provide power flow proportional to rate of change of frequency. The oscillatory nature of power flows for inertia (and for that matter, damping of other small signal oscillations) requires bidirectional power flow at the storage device.

Storage control can be formulated to provide both inertia (proportional to rate of change of system frequency) and damping (proportional to system frequency error). Coordination with load frequency control would provide a mode whereby inertial effects and damping would not be used during system frequency correction, but would operate as needed otherwise.

Earlier in this document, multi-services operation for storage was described. The inertia/damping mode would add another capability that could be view as a grid service. Such a service probably should not be lumped under frequency regulation services, as this capability is not aimed at frequency regulation; it is aimed at grid stabilization and primary generator control.

The foregoing raises some issues:

- Should virtual inertia be classified as an ancillary service?
- If so, how should it be valued? Should there be a market for stabilization services including inertia? The value analysis above indicates that the value of inertia accrues to the system operator.
- Given that in the Western Interconnection, system inertia varies by sub-region, the value of a virtual inertia augmentation service should vary by location.
- Present technology for measuring system frequency works well for steady state conditions, but not for transient conditions, and measurement of rate of change of frequency applies only during transient conditions.
- Can other asset besides storage provide virtual inertia? Can buildings be used to provide incremental grid inertia?
- Given that no single device could provide very much incremental inertia, how could multiple resources be combined?
- If storage or other assets that could augment system inertia are connected at the distribution level as DER, how are the reliability aspects coordinated in the absence of something like a DSO?

At present, technical, market, and regulatory gaps exist for use of storage for system inertia augmentation.

6.2 Electricity/Natural Gas Interaction

The growth of natural gas as fuel for generation is well known, as is its relationship to shale gas extraction. Also known is the fact that gas production, processing and delivery to electric generation uses electricity at many points in the chain. See Figure 6.2 below for an illustration.

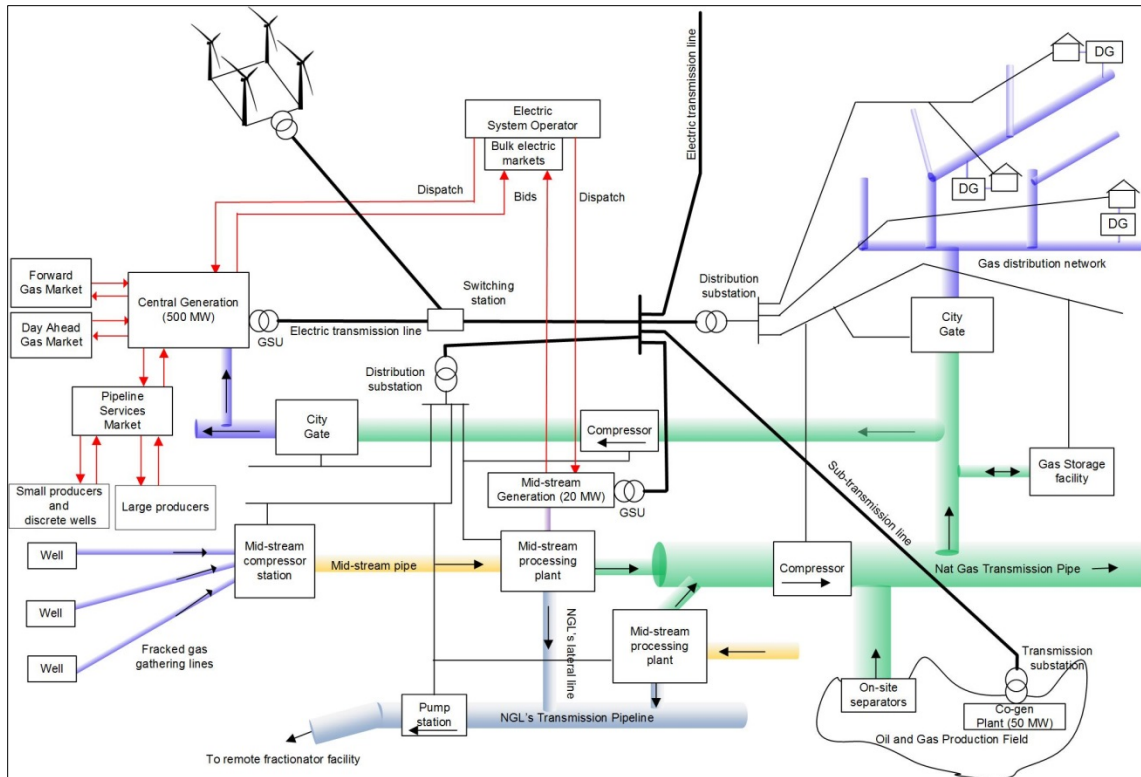


Figure 6.2. Electric and Gas Infrastructure Overlay

The interdependency of gas and electricity can be addressed via multi-fuel strategies. However, the potential exists for the formation of isolated loops, such as shown in Figure 6.3.

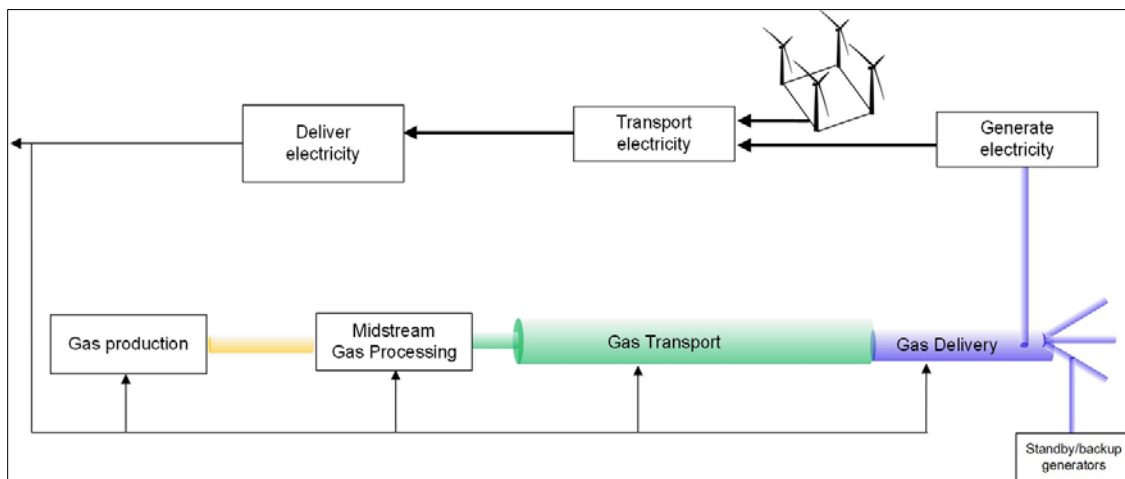


Figure 6.3. Loop Isolation in Gas/Electric Networks

Such a loop condition compromises resilience in two ways:

- The obvious way is that an interruption in the loop can cause electric outage.
- The less obvious way is that such an outage compromises the residential and commercial standby generators that use natural gas for fuel.

In addition, variability in electric supply (from say, wind) causes reduction in flexibility in gas pipeline capacity.

A recent development related to gas/electric interdependence is the rise of midstream generation. While this was conceived as a means to help smaller gas producers who could not secure pipeline capacity get to a market, it has another impact, as seen in Figure 6.4.

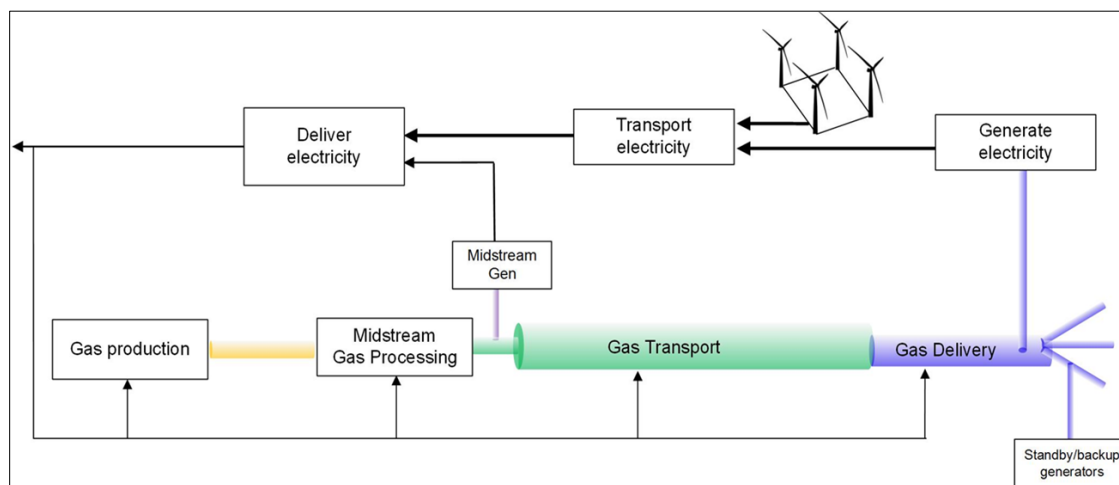


Figure 6.4. Effect of Midstream Generation

Midstream generation causes the formation of another loop inside the main loop. This has the effect of potentially restoring some of the resilience lost due to the isolated loop effect, since faults downstream in gas transport and upstream in electric transport do not have to affect midstream generation. In addition, midstream generation relieves congestion in both gas transmission and electric transmission. The foregoing analysis is simplified, and it would take detailed engineering studies to determine if the loop effect has happened or can happen in a given instance, and whether midstream generation is positioned to mitigate the resilience effects of such a loop. Joint planning for gas and electricity has the potential to capitalize on the potential benefits to resilience by making use of the inner loop effect, as well as breaking up the outer loop effect.

Given some of the statements made by PJM, MISO, and the Western Interstate Energy Board,³⁰ it appears that gas (especially shale gas) and electricity are undergoing more than just integration; this appears to be the beginning of a *convergence*.

Convergence is the transformation of two or more networks or systems to share resources and interact synergistically via a common and seamless architecture.

Early stage convergence drives tighter coupling of network (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 seen above, then 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

³⁰ FERC Gas-Electric Coordination Quarterly Report to the Commission, Docket No. AD12-12-000 September 18, 2014

happening yet, it is worth being aware of the possibility so that convergence is not unnecessarily hampered and innovation can occur.

6.3 Advanced Flexible Distribution

Existing distribution grids have limited flexibility in most places, due to the prevalence of radial feeders, limited feeder interconnection, limited use of looping and inter-ties, and use of simple switching as the primary means of flow control. Dense urban circuit meshes and spot networks are different but have their own limitations, as noted above. For those areas where significant penetration of DER is expected, the constraints created by existing distribution circuit structure limit or block potential advanced functionality. Consider the example flexible distribution circuit illustrated in Figure 6.5.

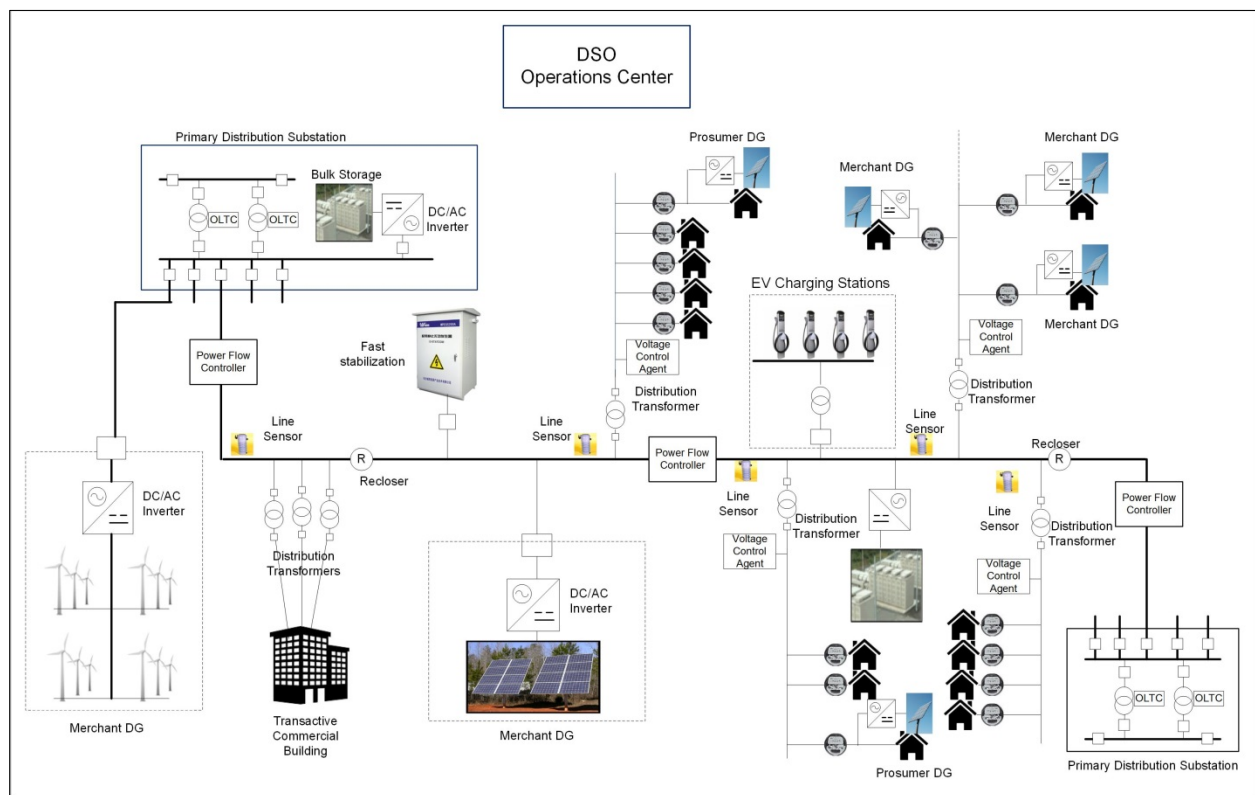


Figure 6.5. Flexible Distribution Circuit

For advanced flexible distribution, apply the following changes:

1. Increase the circuit meshing by providing more feeder primary level interconnections
2. Make selected interconnections via power flow controllers rather than simple switches
3. Provide storage liberally, in primary distribution substations, at the neighborhood level, and behind the meter in various prosumer locations
4. Presume significant penetration of merchant and prosumer Distributed Generation and Demand Response capabilities
5. Make use of the existence of transactive buildings and microgrids

6. Provide a laminar coordination mechanism for the grid devices and connected transactive systems; control is a hybrid of centralized and distributed control
7. Volt/VAr regulation uses a mix of traditional controls (OLTC's), controllable inverters, control agents, and fast stabilization
8. Use the DSO model for distributed reliability, meaning in this case that the DSO manages the power flows after receiving a dispatch from the ISO

With this arrangement, power can be derived from a variable mix of grid and local sources. When excess energy is available from the DG sources, it can be parked in community storage, and then “loaned” to those that want it. The power flow control scheme allows power from one substation’s feeder to be directed to a connected feeder from another substation, where the community storage happens to be attached. Power flow control also provides a means to prevent local voltage control agents from causing unscheduled reactive power flows back into the bulk system, and to prevent faults on one feeder from causing sympathetic trips of circuit breakers on adjacent feeders that have high levels of DG in operation, thus relaxing some of the constraints imposed by traditional distribution circuits.

The utility can use substation level storage to “line pack” when bad weather indicates the likelihood of outages, much in the same way that gas companies can do line packing in the gas lines. During reliability events, the circuit can act as a local energy network, even if no explicit microgrids are present. Transactive buildings can provide services to the grid as long as distribution grid does not have blocking factors such as network protectors in place.

Finally, the availability of storage, DG, and DR with flexible flow control and distributed reliability coordination allows maximization of the benefits of renewables by decoupling the volatility of sources and loads without imposing a massive communication scalability issue upon the ISO.

7.0 Conclusions

The grid is a complex network of structures that has evolved over the past century, driven by a patchwork of regional economic prerogatives, diverse business models and variable regulatory structures. A number of current trends including the convergence of electricity and natural gas infrastructures, and the bifurcation of generation—the emerging split of generation between bulk transmission-connected generation and smaller distribution-connected resources—are adding additional complexity, as well as providing potential opportunity to create new value streams and enhance system resilience.

Grid architecture is a strong tool for managing this complexity, communicating with key stakeholders, identifying science and technology gaps and cross-referencing likely, future industry structure with emerging business models. Leveraging the discipline inherent in the exercise of this architecture is a key means of actively shaping the grid of the future. While legacy investment and regional differences will no doubt influence the path forward for grid modernization, a rigorous review of existing architectures can highlight emerging interactions of key grid functions previously considered in isolation, help avoid stranded investments in infrastructure, and illustrate structural barriers to enhanced resilience and economic value streams.

While limited in scope, this paper’s consideration of select views of current grid architecture provides a number of key insights relevant to emerging trends, specifically with respect to industry structure, business/value streams, electric/power system structure and control/coordination frameworks.

7.1 Industry Structure

- Geographic-based structures have shaped the evolution of the electric power industry over the past century. However, the deployment of more non-utility assets interacting with the grid and emergence of merchant and prosumer-controlled distributed energy resources operating as a set or group despite wide geographic dispersal can erode the concept of a geographically bounded customer.
- A review of industry structures shows that distribution operations are disconnected from the rest of the system in a control and coordination sense. In certain contexts, however, system operators at the wholesale level had already begun bypassing distribution utilities to directly engage distributed energy resources in the last few years. Recent court rulings and industry deliberations on the future of distribution have already opened up reconsideration of roles and responsibilities for ensuring system reliability, especially at the distribution level and have implications for grid control and coordination structure. However, many state and local laws and regulation would have to be changed.

7.2 Business/Value Streams

- Modeling the accrual of value streams within industry structures helps illustrate the kinds of business ecosystem partnerships required to realize such value. Regulatory variables figure prominently in determining which entities can realize such value, and what forms these values (products or services) may take.
- Low-growth value streams are those most directly connected to provision of electricity as a regulated commodity; whereas potential high-growth streams are tethered to customer/prosumer products, devices, and services. Once again, what value streams are regulated, by whom, and under what

terms, will bear on the distribution of these opportunities in what is essentially a zero-sum situation, and what entities are positioned to capture shares of the sum.

7.3 Electric & Power System Structure

- The structure of the grid determines important system properties and basic limits. For example, in major cities, the structure of dense underground urban mesh underlying the distribution system limits any services that buildings might supply to grids to the local feeder secondary, except for those that reduce net load. In these contexts, distributed generation and storage cannot push power back into the distribution feeders, and thus cannot push power to the grid. Furthermore, tripping of multiple network protectors will cause a portion of the secondary mesh to island. Since the network protectors are not coordinated, the extent of the island is unpredictable. Where fuses are used in the secondary, some of these may blow, requiring truck rolls to replace before normal operation can be restored.
- The enablement of two-way flows within distribution systems in the face of such structural limitations can have costs that go beyond those related to new premises equipment and software. Some amount of change at the utility level may be needed just to unblock the potential for certain building-to-grid energy/power services.
- While basic coupling occurs electrically at multiple levels in the grid, coupling can and does occur in other ways, some of which can be quite subtle. Coupling can occur through controls, markets, communications networks, fuel systems, loads, and social interactions of customers/prosumers. Unsuspected coupling is a hazard of increasing grid complexity.
- The list of interactions between system elements is growing as the penetration of new devices and functionality increases. Responsibilities for reliability management have historically been established hierarchically, starting with wholesale generation/transmission treated in a semi-integrated fashion, but then separately at a lower level within distribution—where reliability requirements have historically been assigned to single regulated entities. Two-way power flows within distribution systems will require greater focus on making more explicit shared responsibilities for reliability management (and supporting investments) between distribution system operators and loads/producers within that distribution system.
- Another structural consideration relates to system inertia and coupling of generators with droop control through the transmission system, which is crucial to proper grid operation. The implications for system inertia associated with replacing traditional forms of central station generation with DG and variable resources are not thoroughly understood. This is particularly the case in the loosely coupled Western Interconnection. Exploring methods for measuring—and potentially predicting—system inertia associated with existing operations as well as in context of a changing generation mix may provide key insights for policymakers and regulators concerned with system reliability. At present, this may require additional R&D efforts. In addition, such methods would be useful in the development of joint planning tools, which likewise do not yet exist for purposes of enhancing industry and policymakers' understanding of emerging infrastructure interdependencies (such as electricity and natural gas). Meanwhile, efforts underway in ERCOT to consider inertia-related grid services merit careful attention. Novel configurations of assets at the distribution level (including storage) may ultimately be leveraged to help provide such services—but once again, regulatory friction associated with determining which entities are eligible to provide such services, and allocation of costs and benefits, may once arise under current law.

7.4 Control/Coordination Framework

- The inclusion of markets inside closed loop grid controls means that markets could contribute to control instability. The problem will worsen with additional entities in the loop and the presence of faster dynamics and diverse sources of net load volatility.
- Consider the isolation of distribution control and coordination from the rest of the grid in the light of regulatory structure, namely the Federal regulation of the bulk power system, versus State and local regulation of distribution grids. Note that regulatory structure, industry structure and control/coordination structure are currently aligned—but this alignment is with a control structure that is increasingly problematic as the grid changes due to emerging trends.
- In particular, the changing nature of system dynamics, implications of DER deployment at increasing scale, new technologies and models of consumer engagement are putting pressure on regulatory boundaries drawn over the past century. Current academic and industry literature suggests a consideration of a new, Distribution System Operator (DSO) model, though this thinking is very new and includes a highly varied set of topics.

7.5 Grid Architecture 2030

In addition to reviewing today's grid in the context of emerging trends, architecture is also an useful tool for projecting potential forward-looking alternatives to selected grid structures and components, particularly in light of the widening gaps between existing structure and desired qualities of the future grid.

With desired grid qualities in mind, as specified by DOE—specifically, security, safety, minimal environmental footprint, robustness, flexibility, affordability and financeability—it is possible to make a preliminary review of key architectural elements and derive a number of insights:

- **Buildings:** Buildings are significant users of electricity. Today, they exist primarily as passive loads, but hold promise for potentially providing services back to the grid in a transactive mode. The key grid-side factors limiting the expansion of building-to-grid services are not interoperability or interface standards (important though these are) or quantification of value streams. Instead, they are structural limitations to the distribution grid (such as those previously discussed in context of dense urban mesh), and current lack of a coordination mechanism on the grid side that extends across the grid/building boundary.
- **Storage:** Storage is unique in that it can be capable of taking energy or power from the grid, adding energy or power to the grid, and supplying a wide range of grid services on short (sub-second) and long (hours) time scales. It can supply a variety of services simultaneously. There is an emerging sense that the combination of fast bilateral storage, flexible grid interface mechanisms, and advanced optimizing control is *a general purpose grid element as fundamental as power transformers and circuit breakers*. One of the most significant impacts of storage will be the ability to *decouple generation and load volatilities*. Since it is known that the impact of storage can be location-dependent, there is a need for new planning tools and procedures to make use of storage as a standard grid component, and to optimize storage location and size.

- **Whole Grid Coordination (Laminar Coordination Framework):** Coordination is the means by which distributed elements are made to cooperate to solve a common problem—in this case, grid control. It is clear that existing grid coordination has gaps and lacks a rigorous basis—and that the gap is widening, with respect to grid behavior and desired capabilities. Where the grid is concerned, a structure that accommodates multiple simultaneous approaches to control is likely required. ***Local optimization inside global coordination*** is a principle for a mix of centralized and distributed control that provides properties such as boundary deference, control federation, disaggregation and scalability.
- **ISOs and DER Dispatch:** In certain (but not all) markets today, DER is being dispatched by Independent System Operators, which retain system balancing and reliability responsibilities at the transmission level, and also operate wholesale markets. The Independent System Operator approach has led to several problems that have caused industry to seek alternative arrangements. For example, letting an ISO handle DER causes a bypassing of distribution operators, which introduces ambiguity in the responsibility for distribution reliability, compromising the ability of the distribution operator to manage its assets and operations. A recent 3rd Circuit Court of Appeals ruling, a position statement by PJM, and proceedings in California and New York are addressing these issues. Second, as the number of devices that can participate in the markets and grid operations grows, a scaling problem arises in terms of communications, as well as in the complexity and computational requirements associated with control mechanisms (and associated latency requirements).
- **DSO Structure:** While motivated by the need to clarify and simplify responsibility for distributed reliability, the emerging thinking around a distribution system operator (DSO) model appears entirely consonant with a laminar coordination structure. Since the laminar structure was motivated by the need for whole grid coordination with a rigorous basis for predicting properties such as scalability, it is reasonable to expect that the DSO model can share those properties that derive from such structure. If the DSO were to be implemented as an independent DSO (IDSO), then the IDSO may have issues of economy of scale sufficient to be viable and related cost problems.
- **Power Electronics/AC Power Flow:** There are several means to adjust power flows in AC power systems, including phase shift transformers, variable frequency transformers, and various forms of power electronics. Power electronics get attention as edge connection tools, in the form of inverters for solar PV and storage, but can be used internally in the grid for power flow control.
- **Flexible Electric Circuit Operation:** Adjustable flow control can be used to provide flexibility in electric circuit operation. It can also be used to cut or limit the effect of some kinds of constraints that exist in present circuits, such as unwanted cross feeder flows or unscheduled flows to the transmission system. Meshing provides more paths for power flow (with flow controllers directing the “traffic”), such that it becomes possible to make more effective use of storage and distribution level DG. That means the cost effectiveness of such assets is enhanced two ways: better sharing of the assets, and enablement of new value streams and innovations. At present, distribution grids suffer from poor observability given their lack of sensing capability. Additional efforts to develop observability strategies and tools for design of distribution sensor networks would likely further enhance flexible circuit operations.
- **Policy Implications:** The fundamental policy issue that requires consideration pertains to what kind(s) of entities will be charged with responsibility for designing and operating the distribution system in the future, given the changing landscape. Key questions include the scope of

responsibilities for traditional distribution utilities versus third parties increasingly engaged with the system; the public and private interest objectives that must be served, and how incentives can be created to ensure these objectives are appropriately and efficiently pursued. Additional R&D is required in support of new tools for distribution planning and design, for purpose of addressing emerging needs for enhanced flexibility and resilience—particularly in light of emerging trends. Likewise, regulatory policies should be examined, for purposes of encouraging synchronized measurement at the distribution level, along with investments in asset configurations (storage, substation-level distributed generation, etc.) that will enhance resilience and generally establish distribution as an innovation.

In summary, grid architecture is a powerful tool that can be used to illuminate important grid characteristics. Among these are any limiting factors to the deployment of new distributed technologies and assets – allowing insight from federal and state policymakers. These limitations may combine with a lack of clarity on responsibility for reliability measures to prevent utilities from easily responding to emerging challenges to system resilience.

One solution to the problem of existing system limitations is whole grid coordination. With whole grid coordination, the gap between the bulk and distribution systems can be resolved in a rigorous and scalable manner. This approach is also compatible with existing and emerging approaches to distributed grid control.

The combination of fast storage, advanced optimizing control, and power electronics can become a grid component that can enable the distribution grid to become a general platform for energy value stream innovation. For example, initial architecture review suggests that selective use of power electronics to control distribution power flows may mitigate electric coupling issues at many levels of the grid.

Finally, further development of a forward-looking grid architecture can highlight key science and technology gaps, inform potential policy deliberations and serve as a continuing means of engaging industry stakeholders, key to advancing grid modernization initiatives.

Appendix A - Architectural Principles

Basic system architecture is driven by a set of principles that include:

1. A good architecture is one that meets the needs of the stakeholders (especially the users) to their satisfaction, does not violate established principles of system architecture, and takes into account the relevant “ilities” by allowing for maintenance, evolution, further development, embedding, etc. as the customer requires.
2. Good architectures have conceptual integrity (intellectually clean of unnecessary complexities or 'exceptions,' similar problems are solved in similar ways, etc.), can direct a builder to cost-effective structures that can be completed within a reasonable time frame, conceptually pleasing to all stakeholders (especially the user), and provide some special advantage (such as a competitive advantage) or utility to the customer.
3. Essential functionality drives complexity, not architectural “elegance.”
4. The architect must be cognizant of the global system when optimizing subsystems.
5. Stakeholders should be involved in the process as much as possible, giving frequent and honest feedback on all aspects of the system architecture.
6. Each component should be responsible for only a specific feature or functionality, or aggregation of cohesive functionality. Therefore, component responsibilities should not be allowed overlap or conflict due to structural reasons.
7. The system architect is not a generalist, but rather a specialist in managing complexity.

Grid architecture adds some specifics to the list above:

1. The grid is not an electric circuit; it is a **network of structures**, highly coupled and replete with constraints. Changes to grids must account for impact across the set of structures, not just in limited siloes.
2. Grids are not just complex; they must be viewed as Ultra-Large-Scale Systems,³¹ with the attendant characteristics and implications.
3. Grid architecture in the US is brownfield. Legacy exists and must be dealt with.
4. Work Through the Tiers—as a consequence of the brownfield nature of US grid architecture, given the physical, geographic, and regulatory structures, scaling issues suggest that hierarchy will continue to play a role.
5. Grid architecture involves more than enterprise IT; a wide range of disciplines are needed due to the variety of structures that are involved, including industry, regulatory, electric/power systems, control, communications, sensing and measurement, computation, data management, and increasingly, non-utility elements such as buildings, microgrids, transportation, and fuel systems.
6. A primary focus in grid architecture is on control and coordination; this is partly a result of ultra-large scale complexity issues.

³¹ Mark Klein, Linda Northrop, et. al, Ultra-Large-Scale Systems, Software Engineering Institute, Carnegie-Mellon University, 2006.

7. Grid control and coordination are strongly related to industry structure and to markets where they exist.
8. Coupling through the grid, as well as through other modes, place significant constraints on feasible functionality. Constraints may be cut, but this must be planned, not assumed.
9. Bottom-up approaches to changing the grid result in much more emergent behavior than rigorous systemic approaches; emergent behavior and its consequences are not desirable in a highly connected environment that is shared by many users and is dedicated to reliability and predictable performance. In other words, emergent behavior shouldn't.
10. Local Optimization Inside Global Coordination—grid control make take many forms, but a means for coordination across system and organizational boundaries must be provided. Such a means must have the following properties:
 - a. Control federation—combining and resolving multiple competing and possibly conflicting objectives
 - b. Control disaggregation—decomposing broad control commands into forms suitable for local consumption, taking into account local constraints
 - c. Boundary deference—explicit recognition of system and organizational boundaries, with means to accommodate rather than override such boundaries
 - d. Local selfish optimization—means to enable local optimization goals and constraints within the global coordination framework

Appendix B - Glossary

AMI—Advanced Metering Infrastructure—systems that use two way communications to read utility meter data remotely and automatically and perform other related functions

B2G—Building to Grid—refers to the interaction of buildings and grids, wherein services may be exchanged in either direction

Balancing Authority Area—the region managed by a Balancing Authority for generation dispatch and balance, power interchange with neighboring Balancing Authority Areas, and load frequency control

DER—Distributed Energy Resource(s)—small scale distributed generation and storage, usually connected to a distribution grid. Some definitions also include Demand Response (see responsive load below) in DER

DG—Distributed Generation—electric generation that is not centralized and connected to Transmission, but rather is decentralized and connected to Distribution; individual units are typically much smaller in generation capacity than centralized generation plants

DR—Demand Response—FERC defines DR as “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized”

DSO—Distribution System Operator—A single entity that operates each local distribution area and is responsible for providing reliable real-time distribution service, including the operation of DER. This could be an incumbent Distribution Provider or a new independent entity.

Fast bilateral storage— This is a designation for energy storage for the grid having symmetric characteristics in terms of charging and discharging and capable of responding to fast grid dynamics. Electric batteries combined with power electronics and advanced controls constitute fast bilateral storage; pumped hydro storage does not.

Islanding—the process whereby a microgrid separates itself electrically from the main power grid and operates independently, using its own internal power source(s); it may later rejoin the main grid

Laminar Coordination –the name for a coordination framework for distributed systems that keeps the individual elements aligned on solving a common problem. The Laminar approach uses structure derived from the layered decomposition/network utility maximization approach developed to provide a formal basis for network architectures.

Load frequency control—automatic generator control aimed at regulating system frequency in a closed loop manner, usually on a Balancing Authority Area basis.

Microgrid—Microgrids are electricity distribution systems containing loads and DER, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

OLTC—Online Tap Changer—a substation level device that raises or lowers feeder voltage by small amounts, for voltage regulation purposes

PUD—Public Utility District—a special purpose jurisdiction that provides public utility services

Reactive power—power flow in AC electric networks caused by misalignment of voltage and current waveforms; this misalignment is usually due to the type of load on the circuit and causes a power flow that moves back and forth in a circuit but does not get consumed by the customer. Reactive power flow causes undesirable effects in the power grid but does not generate revenue for the utility.

Recloser—distribution primary feeder protection device that operates by opening a circuit briefly and then reclosing to see if the fault has self-cleared; it repeats this process a programmable number of times before locking out entirely if the fault does not clear. It improves average reliability by avoiding whole feeder circuit breaker trips for small temporary faults.

Responsive load—customer load that can respond to signals from the utility to aid in grid operations; commercial building and residential Demand Response (DR) are two conspicuous examples.

Solar PV—Solar Photovoltaic—technology for generating electricity directly from sunlight using the photovoltaic property of silicon

T&D—Transmission and Distribution—the “wires” part of the grid

Transactive Building—a building that participates in grid management by supplying services to the grid in a transactive energy mode; transactive energy refers to techniques for managing the generation, consumption or flow of electric power within an electric power system through the use of economic or market based constructs while considering grid reliability constraints. The term "transactive" comes from considering that decisions are made based on a value. These decisions may be analogous to or literally economic transactions.

VAR—Volt-Amperes reactive—the units in which reactive power is measured (real power consumed by the utility customer is measured in Watts). Volts are the units for the pressure that causes electricity to flow in a circuit; Amperes are the units of current flow.

Appendix C - Basic Quantitative Assessment of Architectures: Map Analytics

C.1 How to Use Architecture Maps

Architecture maps represent the structure of the architecture and as such are crucial to the development of the architecture, as well as its analysis and assessment. Maps are the basis for numerical evaluation of whole architectures, individual architectural elements or subsets, and for differential analysis of competing architectures. This appendix describes the elementary levels of architecture analysis using maps. Such methods can analytically answer questions such as:

- How well does architecture support the desired system qualities?
- How much does any particular architectural element or subset of elements contribute to each desired system quality?
- How do elements costs and benefits accrue to the system qualities?
- How can architectural variations be assessed?
- Which elements are the most important for achieving any system quality or set of qualities?
- How can system qualities be weighted for importance and how does this affect architecture?
- How can two architectures be compared?

C.2 Converting Maps to Contribution Matrices

The first step involves converting the maps to contribution matrices. This is done for both the architectural elements to system properties map (the left matrix **L**) and the properties to system qualities map (the right matrix **R**). A simple example is shown in Figure C.1 below. Each connecting line results in non-negative entry in the corresponding place in the matrix. In the simplest case, presence of a line yields a 1 for the entry, no line results in a zero for the entry.

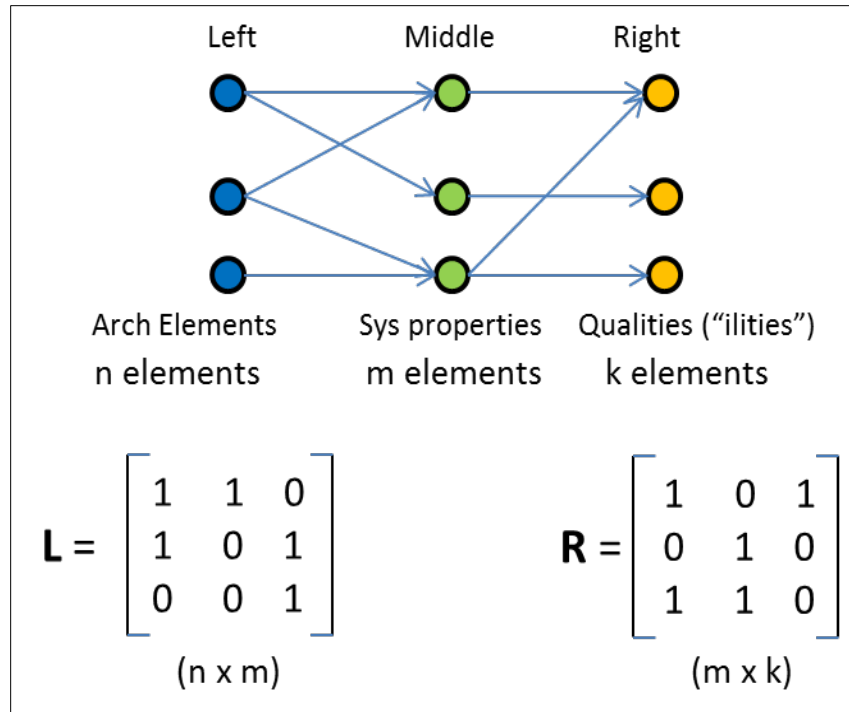


Figure C.1. Converting Maps to Matrices

Next, the matrix rows are normalized, either manually or computationally, as shown in Figure C.2.

$$\mathbf{L}_N = \left[\text{diag} \left[\mathbf{L} \mathbf{1}_n \right] \right]^{-1} \mathbf{L} \quad \mathbf{R}_N = \left[\text{diag} \left[\mathbf{R} \mathbf{1}_m \right] \right]^{-1} \mathbf{R}$$

where $\mathbf{1}_n = [1 \ 1 \ \dots \ 1_n]^T$ and $\text{diag}(\mathbf{X}) = \begin{bmatrix} x_1 & 0 & 0 \\ 0 & x_2 & 0 \\ 0 & 0 & x_3 \end{bmatrix}$ for vector \mathbf{X} of length j

(j x j)

$$\mathbf{L}_N = \begin{bmatrix} 0.5 & 0.5 & 0 \\ 0.5 & 0 & 0.5 \\ 0 & 0 & 1.0 \end{bmatrix} \quad \mathbf{R}_N = \begin{bmatrix} 0.5 & 0 & 0.5 \\ 0 & 1.0 & 0 \\ 0.5 & 0.5 & 0 \end{bmatrix}$$

Figure C.2. Row Normalizing Contribution Matrices

Next, combine the \mathbf{L} and \mathbf{R} matrices into a single transition matrix \mathbf{T} that combines all of the mapping information, as shown below.

$$\mathbf{T} = [\mathbf{L}_N \mathbf{R}_N]^T$$

$$\begin{bmatrix} 0.5 & 0.5 & 0 \\ 0.5 & 0 & 0.5 \\ 0 & 0 & 1.0 \end{bmatrix} \begin{bmatrix} 0.5 & 0 & 0.5 \\ 0 & 1.0 & 0 \\ 0.5 & 0.5 & 0 \end{bmatrix}^T = \begin{bmatrix} 0.25 & 0.5 & 0.5 \\ 0.5 & 0.25 & 0.5 \\ 0.25 & 0.25 & 0 \end{bmatrix}$$

Given the \mathbf{T} matrix, define a vector $\underline{\mathbf{E}}$ of values for the architectural elements and compute the quality vector $\underline{\mathbf{Q}}$ as

$$\underline{\mathbf{Q}} = \mathbf{T} \underline{\mathbf{E}}$$

Choice of values for $\underline{\mathbf{E}}$ provides insights into the architecture.

- To see how a specific architectural element or set of elements impacts the qualities, set the corresponding $\underline{\mathbf{E}}$ values to 1 and the rest to zero and calculate $\underline{\mathbf{Q}}$.
- To see how costs or benefits of architectural elements accrue to qualities, set $\underline{\mathbf{E}}$ values to the costs or benefits and calculate $\underline{\mathbf{Q}}$.

To account for the relative importance of system qualities, define a weighting vector $\underline{\mathbf{W}}$, and calculate a score s as

$$s = \underline{\mathbf{W}}^T \underline{\mathbf{Q}} \quad \text{where vector } \underline{\mathbf{W}} = [w_1 \ w_2 \dots w_k]^T$$

and where the values of w_i are non-negative and add to 1.0. Then

$$s = \underline{\mathbf{W}}^T \mathbf{T} \underline{\mathbf{E}} = s(\underline{\mathbf{E}})$$

So s is a function of architectural elements and can be used to evaluate architectural tradeoffs. More sophisticated scoring can be done by building up metrics from the basics above. For example:

$$s = \underline{\mathbf{W}}^T \underline{\mathbf{Q}}(\text{benefits}) / \underline{\mathbf{W}}^T \underline{\mathbf{Q}}(\text{costs}) = \underline{\mathbf{W}}^T [\mathbf{T} \underline{\mathbf{E}}(\text{benefits})] / \underline{\mathbf{W}}^T [\mathbf{T} \underline{\mathbf{E}}(\text{costs})]$$

To compare competing architectures, as opposed to just incremental changes in a single architecture,

- Set the values of \mathbf{R} and $\underline{\mathbf{W}}$.
- For each architecture, write an appropriate \mathbf{L}_i .
- In some cases, a new \mathbf{R} may be required, depending on how much the architectural approaches differ.

- For each architecture, compute the \mathbf{T}_i matrix, as well as values of \underline{Q}_i and any scores s_i .
- Compare architectures on the basis of the scores and analysis of \underline{Q}_i vectors for equivalent cases across the entire proposed architecture set.

Other more sophisticated analyses are possible, based on analyzing and interpreting the structure of the \mathbf{T} matrix, which encodes a good deal of information about the architecture.

Appendix D - Definitions of DOE Desired Grid Qualities

Minimal-environmental footprint—energy systems should be designed, constructed, operated and decommissioned in a manner that is low carbon and with minimal impact to water quality and quantity; and minimizes the land use footprint, impact on biological resources, and toxic emissions.

Affordability—ensures system costs and needs are balanced with the ability of users to pay. (Note three potential balancing points: overall system costs, system needs/benefits, and system cost allocation). Also, estimating avoided costs can be more complex than for simple levelized costs— calculations require tools to simulate the operation of the power system with and without any project under consideration.

Flexibility—energy infrastructure that accommodates change in response to new and/or unexpected internal or external system drivers. Sub-characteristics of flexibility included:

- Extensibility. The ability to extend into new capabilities, beyond those required when the system first becomes operational.
- Interoperability. The ability to interact and connect with a wide variety of systems and subsystems both in and outside of the energy sector.
- Optionality. Provides infrastructures or features of infrastructures that would allow users to maximize value under future unforeseen circumstances.
- Robustness. A robust energy system will continue to perform its functions under diverse policies and market conditions, and has its operations only marginally affected by external or internal events. Sub-characteristics of robustness include:

- Reliability. Sturdy and dependable, not prone to breakdowns from internal causes (e.g., due to component failures);
- Resiliency. The ability to withstand small to moderate disturbances without loss of service, to maintain minimum service during severe disturbances, and to quickly return to normal service after a disturbance.
- Scalability. Energy infrastructure should be able to be sized to meet a range of demand levels. Systems can be scalable by being replicable, modular, and/or enlargeable.
- Safety. Energy systems should be designed, constructed, operated and decommissioned in a manner that reduces risks to life or health.

Appendix E - Fundamental Basis for Laminar Coordination

The underlying basis for the laminar coordination structure is based on three concepts:

1. From control engineering, the concept of model decomposition
2. From network engineering and economics, the concept of network utility maximization
3. From optimization theory, the concept of convex relaxation

The basic model for the decomposition of an optimization problem is shown in Figure E.1. Its mathematical basis is referred to as layered decomposition via network utility maximization.

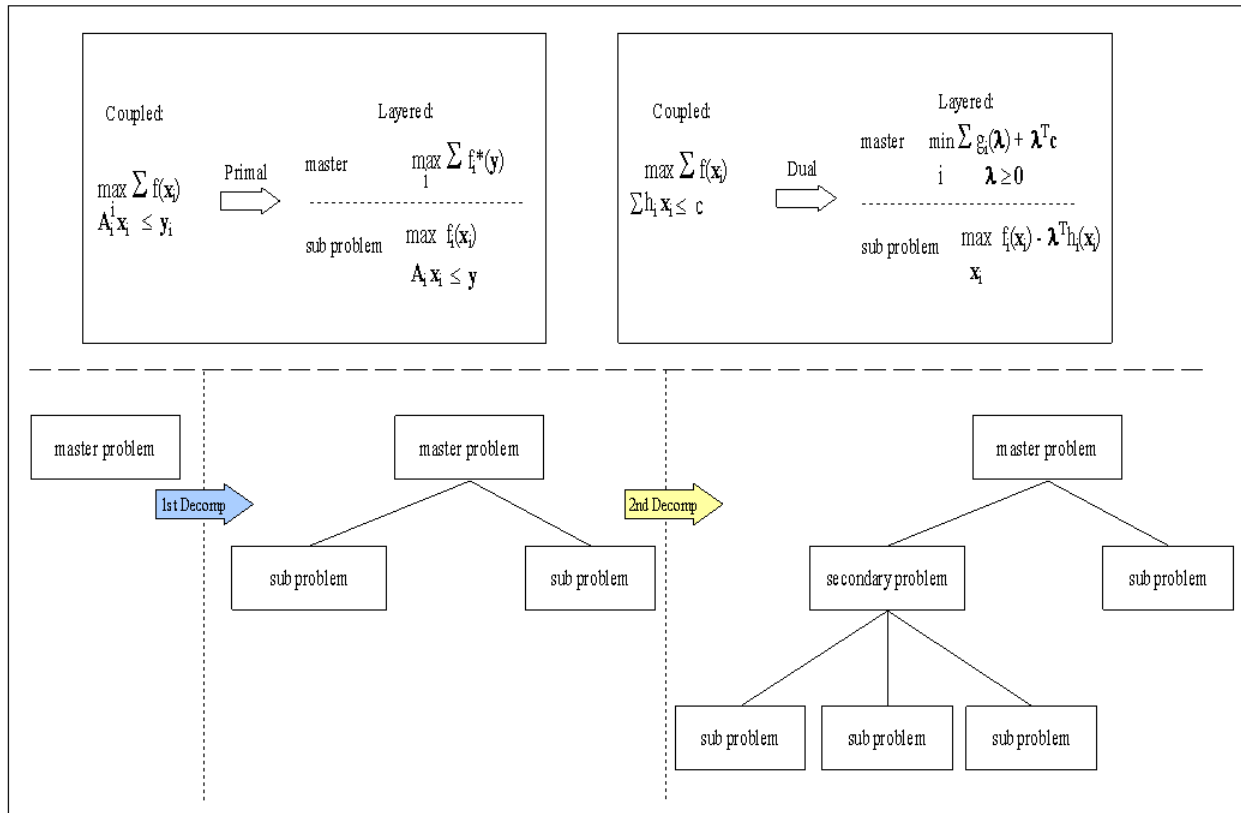


Figure E.1. Layered Decomposition

This is where the basic structure, including self-similarity at differing scales originates. An arbitrary number of decompositions can be employed, which is the origination of the boundary deference property. Decompositions are in one of two forms:

- **Primal**—where coordination is via resource allocations (think dispatch)
- **Dual**— where coordination is via signals that behave as prices (not necessarily currency)

Decompositions may also be mixed and hybrid and so considerable flexibility in formulation is available. The resulting problems are solved in a distributed manner, with each level of computation

getting simpler as the decomposition proceeds (i.e., at lower levels less computing power is needed).³² In other words, at device level, computations are very simple. At the system level, they are more involved but not enormous, since the problem has been decomposed and distributed computing is employed. Since the problems may still be non-convex and therefore hard to solve, a process called convex relaxation can often be applied to obtain useful solutions efficiently. Figure E.2 shows an example of how to map the decomposition onto grid structure. Any grid structure can be handled this way, even the so-called flat structures.

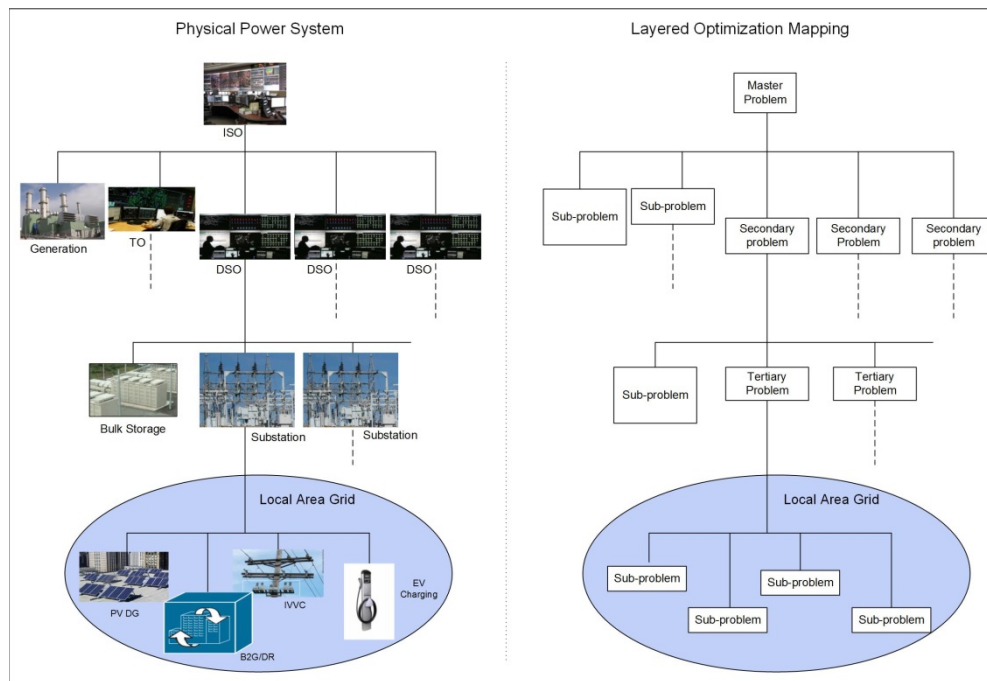


Figure E.2. Mapping Layered Decomposition to the Grid

Layered decomposition provides the basis for a mechanism that allows local selfish optimization (introducing goals and constraints at each node) as well as command disaggregation. The structure can apply not just to the grid, but can be continued down inside a microgrid or a building, for example.

The coordination network that results from this approach has a structure whose properties can be linked back to the underlying mathematics, thus providing a rigorous basis for the structure and an understanding of its properties.

³² Daniel P. Palomar and Mung Chiang, “Alternate Distributed Algorithms for Network Utility Maximization: Framework and Applications”, *IEEE Transactions on Automatic Control*, Vol. 52, No. 12, December 2007.

Appendix F - Works Reviewed for This Project

During the course of this work, a variety of previous and current works related to aspects of grid architecture were reviewed. This appendix contains the list of those works.

Table F.1. Reviewed Prior Works

Architecture name	Smart Grid Reference Architecture - SGRA (2011)
Organization(s)	SCE/IBM/Cisco
Description	IT services-oriented architecture, the primary purpose of which was to create a catalog of services to guide the acquisition of systems and software for smart grid implementations. Primary guiding paradigm was System of Systems (SoS), as opposed to Ultra Large Scale (ULS).
Analysis	Achieved its goal but was weak on control, since it treated control as just one of many applications to be accommodated, thus missing an opportunity to provide real structural insight. Did not address industry structure or markets. Not full grid architecture due to scoping limitations.
Status	Completed
Architecture name	GridOS 3.0 (ongoing)
Organization(s)	EPRI
Description	Proposes modified electrical structures at the bulk power and distribution levels that are modest changes from present structure. Uses the concept of Local Energy Networks (LEN's) at Distribution to generalize the microgrid idea. Treats the LEN notion in a multi-scale manner in that it envisions the same basic LEN approach at the building level as at the campus or neighborhood level. Indicates use of distributed/decentralized control.
Analysis	Work identifies components more so than structures although a key structural idea is embodied in the LEN concept.
Status	Evolving
Architecture name	Smart Grid Reference Architecture and Smart Grid Architectural Model – SGAM M/490 Mandate (ongoing)
Organization(s)	IEC/CENELEC/SGIP
Description	<p>The Smart Grid Reference Architecture provides view from four perspectives: Business, Functional, Information, and Communication.</p> <p>The SGAM Architecture Model is a five-layer abstraction model, with each layer gridded by a cross-hatch of zones and domains (as defined by SGAM). Makes reference to the NIST Conceptual Model and the GWAC Stack (see below). Much of the material is methodology for mapping use cases to the multi-layer abstraction model. It has been promoted as a means to unify various smart grid architectures.</p> <p>SGIP has been gradually taking ownership of this as the Europeans have reduced their activity in this area.</p>
Analysis	Like many such approaches, this is mostly about IT systems and interoperability. This model gives more attention to markets than typical US models do. The methodology can be used to uncover some operational interdependencies, but lacks in structural insights. Siemens makes a tool set for using this model and approach.
Status	Evolving.

As per SGIP: The European Union's (EU) Smart Grids - Coordination Group's (SG-CG) Reference Architecture Working Group used the Conceptual Model and the GWAC Stack as a starting point, and added a third dimension called zones to create the Smart Grid Architecture Model (SGAM). The zones refer to the functional hierarchy of the smart grid: process, field, station, operation, enterprise and market. There has been extremely productive cooperation and collaboration between the North American and EU architecture groups; both have a common goal of maintaining a single architecture model that addresses the commonalities and differences between the regions of the world, and the SGIP Architecture Committee has incorporated the SGAM into its work.

Architecture name	P2030 (2011)
Organization(s)	IEEE
Description	<p>As stated in the document: provides guidelines for smart grid interoperability. This guide provides a knowledge base addressing terminology, characteristics, functional performance and evaluation criteria, and the application of engineering principles for smart grid interoperability of the electric power system with end-use applications and loads. The guide discusses alternate approaches to good practices for the smart grid.</p> <p>Again as stated in the document: this standard provides guidelines in understanding and defining smart grid interoperability of the electric power system with end-use applications and loads. Integration of energy technology and information and communications technology is necessary to achieve seamless operation for electric generation, delivery, and end-use benefits to permit two way power flows with communication and control. Interconnection and intra-facing frameworks and strategies with design definitions are addressed in this standard, providing guidance in expanding the current knowledge base. This expanded knowledge base is needed as a key element in grid architectural designs and operation to promote a more reliable and flexible electric power system.</p>
Analysis	<p>Clearly defines its focus as interoperability, rather than grid architecture.</p> <p>Contains three "Architecture Perspectives": Power Systems, Communication Technology, and Information Systems. None is actually architecture, nor do they appear to be intended as such.</p> <p>P2030 is essentially a catalog of interfaces, with a mostly legacy systems point of view. It does contain a diagram referred to as "Smart Grid Architectural Diagram", but this does not rise to the level of architecture.</p> <p>The effort has produced a document: <i>Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads</i></p>
Status	Some work still ongoing

Architecture name	Smart Grid Conceptual Model (2010)
Organization(s)	NIST/SGIP
Description	Model representation of power delivery chain entities with some amount of functional description and indications of generic interactions; multi-resolution format provides some ability to drill down into entity/functional areas; recommends a peer-to-peer only communications model. Most of the information is depicted in simplified diagrammatic format drawings.

Analysis	Does not contain much on forward-looking views and is weak on structure in multiple areas; some entities not represented; no clear depiction of control structure; does not recognize most emerging trends as of 2014 and does not elucidate impact of trends or identify systemic issues; a static view on what used to be, rather than a workable tool for grid modernization. Communications portion effectively locks utilities into a primitive approach to networking, thus removing many valuable tools (such a PIM/SSM) from the designer's hands and reducing networks to pre-2000 levels of effectiveness. In effect, this model is aging and gradually becoming less relevant to grid modernization.
Status	Completed
<hr/>	
Architecture name	Smart Energy Reference Architecture - SERA (2013)
Organization(s)	Microsoft
Description	This is a solution architecture based on Microsoft products. Most of the rather long (255 pages) document is boilerplate; very little is architectural in nature. Diagram in Fig 58 is as close as it gets to architecture. Much of the document advocates the ESB/SOA design pattern.
Analysis	Essentially a mashup of products on a framework derived from other data management work in the industry.
Status	Completed
<hr/>	
Architecture name	GridBlocks™ (2012)
Organization(s)	Cisco Systems
Description	Communications-centric reference architecture for power delivery chains, from interconnection to responsive load.
Analysis	Includes a model for distributed computation that is based on the ULS Control Architecture white paper that has gotten good traction in the utility industry
Status	Completed; very little on-going support from Cisco
<hr/>	
Architecture name	GWAC Stack (2008)
Organization(s)	GridWise Architectural Council
Description	A stack-based abstraction model for grid information interchange among IT systems.
Analysis	Not an architecture; rather, GWAC calls this an "interoperability framework." Does not address issues of structure at any level, except to the extent that it refers to the NIST domains model.
Status	Completed
<hr/>	
Architecture name	Next Gen Data Architecture (ongoing)
Organization(s)	CURRENT and other participants; ORNL work sponsored in part by DOE
Description	The general scope of the activity is defining R&D gaps in data architectures associated with future requirements for the power grid. With new data sources like smart meters and synchrophasors, there is a general impression that utilities will need help with big data. However, there was an early recognition by the CURRENT team that there is a lot of existing technology that could be applied, and the residual R&D gap may be more in the area of data architectures that can support wide area control. The overall thrust of the approach is to define requirements-driven applications. However, an alternative viewpoint in the group suggests that the data layer, analytics, and decision/control are separate and one should remove the applications development from the data management challenges.

Analysis	This is an early effort, concentrating on data architecture, and specifically for wide area bulk power systems applications. As such, it is primarily focused on PMU data.
Status	Work in Progress; very early in its self-defined process.
<hr/>	
Architecture name	Solution Architecture for Energy and Utilities - SAFE (2009)
Organization(s)	IBM
Description	Defined by IBM as a solution architecture; this is not a reference architecture; but rather, a guide to applying IBM products to selected issues in the utility industry.
Analysis	Original "architecture" was a mash-up of IBM products on a framework derived from IEC 61968/61970 diagrams circa 2005; more recently it has been updated so that the key diagram looks a bit like a cross between the older one and the GWAC Stack, with topics chosen so that IBM products will fit. It does not have the IBM products explicitly listed as was done in the past, which is an improvement.
Status	Finished; some incremental additions over time; some improvement in sophistication have been added since it originated.
<hr/>	
Architecture name	Intelligent Network Data Enterprise - INDE (2009)
Organization(s)	Accenture
Description	Framework that provides utilities with the blueprint, tools, processes, services, databases, analytics and visualization capabilities needed to transform massive volumes of smart grid data into actionable, intelligent information; this is a partial grid architecture and tool set focused on grid data management and processing.
Analysis	Does not address control or industry structure or markets; primarily for management of data from distribution grids and prosumer devices and systems; strong on data management and integration of analytics; weak elsewhere. Focused on legacy systems and approaches for the most part.
Status	Was stagnant for a period of time but now has been licensed to Omnetic (Siemens spinoff with Accenture participation) and is being restructured toward focus on edge analytics.
<hr/>	
Architecture name	TC 57 Reference Architecture (ongoing)
Organization(s)	IEC
Description	Schema for data representation and exchange; provides a rough classification of functions into six categories: SCADA, EMS, DMS, Market Ops, Engineering and Maintenance, and External IT Applications. Provides a stacked set of communication protocols and a middleware layer model that employs the IEC Common Information Model. TC 57 includes the CIM work (IEC 61968/61970) as well as the IEC 61850 family of standards for representation, event messaging, data exchange, and configuration; originally intended for electrical substations, 61850 has grown to encompass PMU's and distribution automation as well.
Analysis	This is entirely an information representation and exchange standard, rather than grid architecture.
Status	Ongoing refinement and extension.
<hr/>	
Architecture name	Utility Communications Architecture - UCA™ (2000)
Organization(s)	IEEE
Description	Standards-oriented schemas for data interchange in utility environments. Intended for

Analysis	multiple industries, not just electric power. The UCA documents specify a set of existing international standards that can be applied to specific communications architectural requirements in the utility industry.
Status	Communications standards only. Considerable overlap in scope with various NIST/SGIP and IEC efforts, as this was an early precursor, started by EPRI and transitioned to IEEE.
Status	Complete.
Architecture name	Grids with Intelligent Periphery - GRIP (2012)
Organization(s)	UC Berkeley, CalTech, WSU, U Fla, U Hawaii, CIEE.
Description	Mostly a rough concept for grid management and control, based on decentralized energy sources and distributed layered control; uses the concept of a "balanced cluster" (very much like a Local Energy Network); defines several entities (architectural components) for the control/management portion of a grid architecture
Analysis	While this is not a complete grid architecture, it does address a key portion: grid control. The layered approach is consonant with other architectural thinking about grid structure and can be connected to mathematical approaches that give rigor to the structure.
Status	Evolving at the conceptual level.
Architecture name	Hierarchical Microgrid Control Architecture (2013)
Organization(s)	Illinois Institute of Technology
Description	Architecture for a microgrid; covers electrical structure and control structure, plus some aspects of data measurement. Argues against multi-agent control.
Analysis	The architecture is basically a microgrid version of grid control as it is known today, with primary, secondary and tertiary controls arranged in a hierarchy. It does feature an approach to having DER units operate autonomously or in groups, and makes use of synchrophasor measurement at the distribution level (there is no transmission level in this microgrid).
Status	Complete.
Architecture name	Layered Decomposition/Network Utility Maximization (2007-present)
Organization(s)	CalTech, Princeton.
Description	Application of formal theory of optimization and networking to grid control; implies control structure and therefore architectural elements. Supports fractal models for grid control and coordination.
Analysis	Theoretical work aimed at providing a rigorous basis for design of networks in general, and grid controls in particular. Several grid control problems have been formulated in this framework and some work has been done in deriving the essential control structure that this work implies.
Status	Evolving at the mathematical formalism level.
Architecture name	Next Generation Agile Grid (2010)
Organization(s)	NRECA
Description	Some architectural concepts related to electrical and control structure; hierarchical cellular electrical structure (referred to in the material as "fractal" because it is advocated for use on multiple spatial scales), with autonomous

Analysis	<p>association/dissociation of cells at the electrical and control levels.</p> <p>Essentially, the model is a grid comprised of a large number of microgrids, acting as cellular automata or coupled map lattices. The fractal issue is incidental, but constitutes recognition that some amount of hierarchy is likely to be used.</p> <p>Some premises, such as "Ideally, any device can be controlled by any computer control node if there is a communications link" represent both security and control coordination issues that are not addressed or resolved. Discusses "optimal distributed control," but does not define the basis or optimization criteria.</p> <p>The available material shows no formal or rigorous basis for the suggested structures - this is more conceptual than architectural. Focuses mostly on flow and resilience, but does not address aspects of grid control other than balance and to some extent Volt/VAr control.</p>
Status	Early stage concept.

Architecture name	IntelliGrid Architecture (2004)
Organization(s)	EPRI
Description	<p>Uses an entity model that defines 20 "environments", distinguished by their security, information, and communication requirements. Power functions are grouped in five categories: Generation, Market Operations, Transmission Operations, Distribution Operations, Consumer Services, and Distributed Resources. The project included an extensive set of use cases, as they stood at the time of this work (still available in a repository). The actual architecture (represented in UML form) has five "viewpoints": Enterprise, Information, Computation, Engineering, and Technology.</p>
Analysis	<p>This work is well done from a methodology standpoint, but is limited to industry and other structures as they were at the time this work was done. Many of the newer trends and systemic issues have emerged since then. Also, control structure is not explicit. Does not consider the effect of network convergences beyond power grid/communications convergence, and does not use formal convergence concepts.</p> <p>Ultimately, this is a smart grid architecture, very IT/communications-oriented, and has aged such that it does not address the some of the newer issues. See EPRI GridOS 3.0 for more recent EPRI approaches.</p>
Status	Complete.

Architecture name	Decentralized Control for Ultra-Reliable Green Electricity Networks: Reference Architecture (2012-2014)
Organization(s)	Georgia Tech/ARPA-E
Description	Control system approach using the notion of abstraction layers similar to but less detailed than those found in the SGAM architecture model. Much emphasis on formulation of optimization problems associated with grid control.
Analysis	While this is not a complete grid architecture, it does address control and to some extent electrical structure. Uses a definition of "prosumer" that amounts to a sort of generalized microgrid, thus departing from the common understanding of the prosumer model. Focuses on this and certain control formulations and is

	fundamentally geared toward a particular implementation (multi-agent systems) that has open territory in terms of realization.
Status	Research

Architecture name	Scalable and Flat Controls for Reliable Power Grid Operation (2010)
Organization(s)	U Tennessee-Knoxville, U Illinois-Urbana Champagne, Northeastern University, Rensselaer Polytechnic Institute
Description	Proposed “flat” control is actually a hierarchical multi-layer control with local closed loop control and multi-layer “contextual” control
Analysis	This is essentially the same model that emerges from layered decomposition but without the formal coordination process foundation.
Status	Research

The items in the table above have had varying degrees of industry adoption. The reasons for this vary from case to case.

Among the most successful have been the IEC Common Information Model (CIM – part of TC57 work). CIM has been widely adopted by utility application system makers. In fact CIM is widely specified by the industry during new procurements and most manufacturers of the relevant systems prominently feature CIM compliance and interoperability. This has caused the smaller device and system suppliers to also incorporate CIM compliance, so that an ecosystem has formed around IEC CIM. The only other thing that is comparable in this regard is MultiSpeak, which is purely an interoperability standard. IEC CIM still has shortcomings and there are efforts to harmonize CIM with MultiSpeak for example, but nevertheless, it can certainly be counted a success and is a key element of the data persistence and interchange portion of grid architecture. Note however, that neither CIM nor MultiSpeak are architectures in themselves; they are data representation and interchange schema. Nevertheless, both are quite successful, with MultiSpeak being widely used by utility cooperatives.

The IEC 61850 family of standards is also relatively successful, although uptake of many aspects of 61850 has been slower in the U.S. than in Europe. This is partly a reflection of differences in utility relationships with vendors between the U.S. and Europe, and partly a reflection of the large investment made in the U.S. in DNP 3.0 and its predecessors before IEC 61850 was well established.

IntelliGrid had some early influence on smart grid due to its solid thinking and strong methodology but has faded somewhat due to its age. EPRI is working on GridOS3.0 as a kind of update, but it is too new to judge what impact that may have.

GridBlocks and UCA are subset architectures for communications for electric utilities. Each has had some success, but in the case of GridBlocks, support is dependent on of the vendor. It uses open standards, as does UCA, and actual network architectures are not tied to specific vendor products, but promotion of the architecture depends on the vendor, as GridBlocks is not a standard itself.

Similar comments can be made about SERA (Microsoft), SAFE (IBM), and INDE (originally Accenture and now Omnetric). These are data management, analytics, and application architecture for smart grids. They have had some small impact on smart grid, but since none is an open standard, they are not widely cited.

The SGRA (SCE) is a bit different in that it was created by a utility. However, it is essentially a catalog of software services for smart grids, and was intended to inform utilities about the sets of services they may

need to acquire software or systems to support. It has not become an open standard and has had little uptake. A somewhat similar approach has been taken by the IEEE for its P2030 standard. This is essentially a catalog of interfaces to be considered in smart grid implementations. While P2030 makes some reference to architecture, there is very little structural content. Together, SGRA and P2030 could be considered a rough implementation guide, but they do not make for consistent or comprehensive reference architectures for the grid.

The GridWise Architecture Council GWAC Stack and the NIST Smart Grid Conceptual Model are not architectures but have had some currency in explain basic concepts related to utility organization (SGCM) and interoperability of information systems (GWAC Stack). The GWAC Stack is being considered for an IEC standard, but it is a conceptual framework, and as such does not lend itself to implementations. That is to say, there are no implementations of a GWAC Stack, as there are of say, an IPv6 stack. Likewise, the SGCM was popular for a time in explaining at a high level how the industry was structured, but it has aged and is becoming less relevant as the grid evolves. Neither has much actual usage in the industry.

The remainder of the items (GRIP, SGAM, Next Gen Agile Grid, Layered Decomposition, Scalable and Flat Controls, and Decentralized Control for Ultra-reliable Green Electricity Networks) are young concepts and have yet to be fully tested in the industry. They have certain common elements and it seems likely that some version of layered and distributed control will in fact be adopted by the industry but it is too early to tell how that will look in practice.

Appendix G - Emerging Utility Industry Trends

During the course of this work, various emerging trends impacting electric grids and the industry architecture were reviewed. This appendix contains the list of those trends.

Table G.1. Emerging Trends

Issue	Explanation	Comments
Increasing data volumes from the grid	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 50,000 Phasor Measurement Units (PMU's) 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 PMU's 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	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

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. Automatic control is necessary and this brings with it the need to obtain data on the same times scales as the control must operate. Consequently, there is a sort of double hit: many more new devices to control, and much faster dynamics for each device, leading to vast new data streams and increasing dependence on ICT for data acquisition and transport, analysis, and automated decision and control.

operators to comprehend at the raw data level.

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 cause effects ranging from reduced effectiveness of a smart grid function, up to and including wide area blackout. Generally, effects of such interactions will not be important at the scale of pilot projects and demonstrations, but will become significant as penetrations pass tipping points.

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

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 is on the radar screens of several utilities such as SCE. Solutions to these problems may involve new types of grid components and controls, and repurposing of older device types with new controls.

	will cause shutdown of coastal gas-fired plants between 2017 and 2022.	
Bifurcation of the generation model	As part of the RPS and VER trend, the generation model for power grids has been shifting from 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.	Causes a split in regulatory jurisdiction as well
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.

Changing fuel mix	<p>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.</p>	<p>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 for generation in unusual peaking conditions is complex.</p>
Evolving industry/business models and structure	<p>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 distribution grid operators as is much thought leadership in the industry at large</p>	<p>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.</p>
Evolving control system structure	<p>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.</p>	<p>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.</p>

Midstream generation	Connection of small (20–30MW) 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 a path to market that was blocked due to gas transmission congestion.	Implications for T&D planning; coordinate 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).	Multiple use cases identified; may also be useful for augmenting system inertia via advanced control.
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. Needed to coordinate multiple controls/objectives. Needed to take complex constraints into account. Needed to solve distributed control problems.

Building 2 grid convergence	Commercial building owners and grid operators are recognizing the potential value of going beyond traditional demand response to allow for two way exchange of energy services.	The issues of building to grid integration involve not only interface specifications but at a higher level, logical functional 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



Pacific Northwest
NATIONAL LABORATORY

*Proudly Operated by **Battelle** Since 1965*

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

U.S. DEPARTMENT OF
ENERGY

www.pnnl.gov