Grid Architecture Specification: Advanced Bulk Power System Reference Architecture

GMLC 1.2.1 v0.1

November 2019

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GMLC 1.2.1 final

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Grid Architecture Specification

View Designation: GMLC 1.2.1 Advanced Bulk Power System Reference Architecture v0.1

Structure Types:

x	Electrical Structure	x	Industry/Business Structure		Regulatory Structure
x	Digital (ICT) Structure	x	Control Structure	x	Coordination Structure
	Market Structure	x	Convergent Networks		Other (name it)

Perspective Types

	Demand/Supply Flow	x	Industry Structure		Value Flow
x	Grid/Circuit	x	Sensing & Measurement	x	Data Mgmt./Data Flow
x	Analytics/Visualization	x	Control/Coordination	x	Protection
x	Communication Networks	x	Timing Distribution		Cyber-Security
	Component Class Specification		Component Allocation Model		Grid Dynamics
x	Market-Control		Computation Resources		Other (name it)

Summary Overview

This document describes architectural (structural) elements for an advanced bulk power system.

Glossary

BPS – Bulk Power System

DER – Distributed Energy Resource

DO – Distribution Operator

DSO – Distribution System Operator

ESO – Energy Services Organization

ICT – Information and Communication Technology

LEN – Logical Energy Network

PFC – Power Flow Controller

PMU – Phasor Measurement Unit

SoC – State of Charge (for electric energy storage)

T/D – Transmission/Distribution

TSO – Transmission System Operator

ULS – Ultra Large Scale

UPFC – Unified Power Flow Controller

VER – Variable Energy Resource

VExC – Volatility Exchange Control

V/VAR – Volt / Volt Amperes Reactive

WAN – Wide Area Network (communications)

Key Emerging Trends List

Document *Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid* contains the list of US utility emerging trends used as input to the architecture development.

Key Systemic Issues List

Document *Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid* contains a list of cross-cutting issues (those affecting whole grids or major portions) used as input to the architecture development. Key issues include increasing need for system resilience, impact of the penetration of wind and solar PV generation, increasing data flow and data connectivity, cyber and physical threats, and the changing role of distribution with consequent issues of Transmission/Distribution coordination.

Problem Domain Reference Model

The problem domain is the existing grid and while that term is broad, the issue has become nearly ubiquitous in recent years and so has application across regions and industry structures. The problem domain is described in detail in *Problem Domain Reference Model – GMLC1.2.1-v2.pdf*.

Scenarios and Point of View

The key scenarios for this reference architecture are:

- Wide area closed loop protection and control
- Electronic stabilization
- Coordination with Distribution systems
- Gas/electric convergence
- Mid-stream generation
- Use of bulk energy storage

- Variable flow control

The point of view in this reference model is regional bulk power systems, possibly including multiple transmission systems. It applies to both restructured regions with ISOs/RTOs/ and non-restructured systems with Transmission System Operators (such as Balancing Authorities or Power Marketing Authorities).

Business Context, Entities, and Relationships

A wide array of entities are involved in the US electric power system. A list of entities and their standard definitions can be found in spreadsheet *Entities.Definitions.01.09.2019*.

The US electric utility industry has a complex set of structures that vary regionally and due to differing types of utilities (Investor Owned Utilities, Co-ops and municipals, Power Marketing Authorities, G&Ts, vertically integrated utilities, etc. as well as system operators, balancing authorities, reliability coordinators and the like). Refer to the following industry structure models:

- California (focus on CA ISO service area): *CA focused industry structure model ER.vsd*
- New York: NY Industry Structure Diagram_v1.2.vsd and NY Industry Structure Diagram_v1.2.xlsx
- Texas with focus on ERCOT service area: *ERCOT Industry Structure Diagram_v1.vsdx* and *ERCOT Industry Structure Diagram_v1.xlsx and ERCOT Market Control_v0.1.vsdx.*
- Pacific Northwest: PNW Industry Structure Diagram_v1.vsdx.

Regulatory/Public Policy Context

Regulations vary widely for distribution, since most distribution issues are regulated at the state level. Some aspects of DER may fall under FERC jurisdiction, especially those related to sale for resale of energy or generation capacity. Many states have public policies and regulations regarding renewable resource portfolios and goals that drive adoption of DER and especially wind and solar PV DG. One state (NY) has declared that distribution utilities will have distribution level DER markets, primarily for the purpose of distribution capacity management by non-wires alternatives, but with other goals as well. In some cases, this must lead to two markets for DER, and competing uses for the same assets. In those cases, resolution of control or coordination is an important issue.

A model for the US electric utility regulatory structure can be found in *Regulatory Structure Model.vsx*.

Objectives

Modernized advanced Bulk power systems must provide, support, or enable elements of Robustness (including observability, operational flexibility, resilience, reliability, and agility).[4] Specifically, the overall objective for this reference architecture is to show how to modify existing grid structure and specify new grid structure as appropriate to accommodate emerging changes in generation and in distribution impacts on transmission, as well as emerging trends in technology and in multi-infrastructure convergence.

The objectives for this reference architecture are to indicate structural approaches that will:

1. Facilitate significant increases in operational flexibility and resilience of bulk power systems.
2. Accommodate emerging trends in generation structural change.

Improve observability, protection, and control of transmission systems.

Core Advanced Bulk Power System Architecture Principles

1. BPS generation is a mix of dispatchable and stochastic assets that must be balanced to meet demand.
2. Whole grid generation has bifurcated and continues to split between centralized BPS transmission-connected generation and distribution-connected generation.
3. At the transmission/distribution electrical interface, distribution behaves as a combination of load and a generation tie point capable of supplying energy and grid services.
4. AC generation will continue to require synchronization and load sharing, so BPS state measurement will require synchronized measurement for grid observability.

General Architecture Principles

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 qualities and properties as the stakeholders require.
2. Good architectures have conceptual integrity (adhering to a set of core principles, clean of unnecessary complexities or 'exceptions,' similar problems are solved in similar ways, etc.).
3. Conceptual integrity is best achieved by a small cohesive team of like-minded architects. Architecture should be the product of a single architect or small team with an identified leader.
4. Essential functionality drives complexity, not architectural “elegance.”

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[4] GMLC Grid Architecture Core Team, Grid Characteristics: Using Definitions and Definition Structure for Decision-Making, PNNL-SA-141678, February 2019, available online: https://gridarchitecture.pnnl.gov/media/methods/Grid_Characteristics_Definitions_and_Structure.pdf

5. Architectural structures should have formal bases where possible to minimize ad hoc configurations with unknown properties.
6. Architecture should not depend on a particular commercial product or tool.
7. Architecture should produce enforceable key constraints.
8. The architect must be cognizant of the global system when optimizing subsystems.
9. Stakeholders should be involved in the process as much as possible, giving frequent and honest feedback on all aspects of the system architecture.
10. Each component should be responsible for only a specific feature or functionality, or aggregation of cohesive functionality. Components should be coupled only through explicit structure, avoiding hidden coupling where possible.
11. Reference grid architectures should inform interfaces.
12. The system architect is not a generalist, but rather a specialist in managing complexity.

Core Architectural Concepts

In addition to the guiding architectural principles, a set of core concepts inform the architecture specifications below.

Situational awareness – the need for situational awareness is fundamental. This involves more than just grid power state. This work uses the concept of Extended Grid State, as defined in the work done in the US DOE Grid Modernization Initiative Sensing and Measurement Strategy project.[5]

ULS normal failures approach – applying Ultra-Large Scale system theory[6] to the grid leads to the view that faults and faults must be treated as normal events rather than exceptions. This includes failures in DER and in communications to DERs as well a general grid failures. Examples include intermittent communication link failures, bad software maintenance and upgrades, noisy and/or missing measurements and any number of other failures that plague large complex systems.

Flexibility, extensibility, and agility – the ability of a system (in this case the grid) to make (usually automatic) adjustments to grid stresses. This can include traditional energy resource flexibility, and increasingly, energy resource flexibility afforded by the use of DER, including net load flexibility. It includes structural flexibility, such as automated capability for fault isolation and circuit reconfiguration. It also includes the ability to change or add functions and behaviors as new circumstances warrant.

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[5] GMLC Sensing and Measurement Extended Grid State Task Team, Extended Grid State Definition Document, PNNL-SA-141027, available online: https://gridarchitecture.pnnl.gov/media/white-papers/Extended_Grid_State_Definition_v3.3_GMLCFormat_final.pdf

[6] Mark Klein, Linda Northrop, et al., Ultra-Large-Scale Systems, Software Engineering Institute, Carnegie-Mellon University, 2006. Available online.

Extensibility, the ability to add functionality without major restructuring, is a key to future-proofing investments and is a legitimate focus for grid architecture. The driving forces in the extensibility case come from at least one of the following:

- Changing customer expectations
- Availability of new technology
- New legislative or regulatory mandates

Structural extensibility is a means to address such trends, by providing the foundation for agility in the implementation of new capabilities. Agility refers to the speed with which either flexibility or extensibility can be exercised.

Multi-Scale Structure – Scalability is always a consideration in developing systems for the grid. In the case of grid structure, it refers to the use of structures that apply equally well at any grid scale, from microgrid up to regional interconnection. We refer to such structures as multi-scale structures, and using such structures is a means of achieving conceptual integrity for the architecture, specifically under the principle of solving similar problems in similar ways.[7]

Multi-scale structures look very similar at any grid scale when viewed graphically. More deeply, the inherent properties of the structure work the same way at any grid scale. Use of multi-scale structures provides re-usable structure template with known inherent properties, including inherent structural scalability.

Distributed "vs." centralized systems – a decentralized system is one in which the elements are separate (usually geographically dispersed but not always) and act independently, with perhaps some small amount of supervision to provide set points, etc. A distributed system is a decentralized system in which the elements cooperate to solve a common problem. This implies some form of communication among the decentralized elements. A centralized system is one in which all of the computing, logic, control, data analysis, etc. is performed at a single element. A centralized system is a degenerate form of distributed architecture and distributed systems may have a central element that participates in the overall processes, this latter being sometimes characterized as a hybrid of central and distributed architectures.

Distributed and mixed entity coordination/control – control of DER, especially grid connected inverters, must fit into a structure that allows for mixtures of DER, for control of DER by various entities besides the distribution utility, and for interpenetration of DER types and entities (e.g. multiple DER aggregators operating in overlapping areas down to the distribution circuit secondary level), as well as direct control by the distribution utility. Communication with the DER elements for purpose of control may be through

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[7] In the science of physics, a physical law must be expressed in the form of tensors so that it is independent of the frame of reference. In the discipline of Grid Architecture, the equivalent is the use of multi-scale structures, so as to be independent of the grid scale (the frame of reference) when solving structural problems.

utility communication networks or through telecommunications service providers and may include the internet. All of these modes of communication and control may co-exist in a single utility service area. In addition to control via an external entity, control may be performed autonomously by any particular DER element or groups of DER elements may associate and operate as coordinated DER networks, either under supervision by an external entity or as an autonomous system. Distribution Automation systems may operate in similar autonomous unit or coordinated autonomous group modes.

Regular repeating structures in control and coordination – in support of the above, and to manage complexity, coordination and control structure must be assembled from defined building blocks that can be used at various scales to compose complete structures (architectures) for coordination and control with sufficient regularity and interface definition to enable both simple DER integration and self-assembly of DER and DA networks.

Sensing/measurement infrastructure layer – sensing and communications for the distribution grid must be structured as an infrastructure layer rather than a set of application silos.[8] The use of a sensing and communications layer facilitates variable grid structure.

Architecture Specifications

The architectural views are presented in terms of (black box) components, structures, and externally visible characteristics.[9] These views are not designs, but can be used as precursors to such.

Key Components

Key component classes are defined in the Component Class Models. They include:

Grid Architecture Component Class Specification – Power Flow Controller

Grid Architecture Component Class Specification – Digital Communication Network

This set is **not intended to be an exhaustive list of component types used in electric power systems**. Rather it is intended to provide definitions of key component types (especially those that are new or are just emerging in importance in electric power delivery systems). Many of these newer component types have multiple or ambiguous definitions; the Component Class Model documents provide clarity on the definitions used in this specification.

Specification 1: Transmission/Distribution Coordination

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[8] J Taft and P De Martini, Sensing and Measurement Architecture for Grid Modernization, PNNL-25249, February 2016, available online: https://gridarchitecture.pnnl.gov/media/advanced/Sensor%20Networks%20for%20Electric%20Power%20Systems.pdf

[9] See http://gridarchitecture.pnnl.gov/basic-terms-and-principles.aspx for explanation of basic terms and concepts.

The purpose of this structure (also called the Market DSO model) is to enable the TSO to use distribution connected assets (DER) for grid resilience and operational flexibility purposes. This structure derives from layered decomposition considerations and resolves issues of scalability, tier bypassing, and hidden coupling while limiting the exposure of the transmission system operator to cyber vulnerabilities, as compared to flatter structures. Figure 1 illustrates the basic DSO/TSO structure.[10]

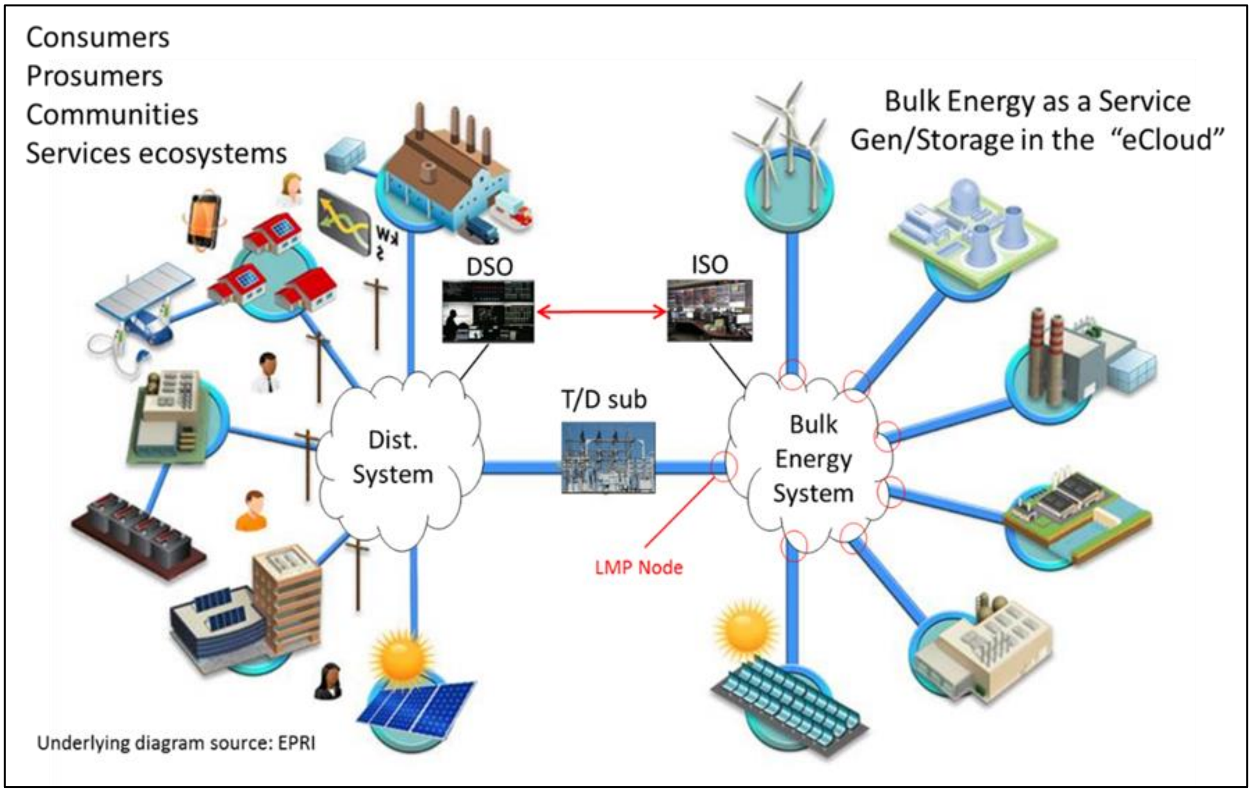

Figure 1 Total DSO/TSO Industry Structure Model

Note that from the perspective of the transmission system operator, a distribution system looks like a combination of traditional load *plus a generation tie point, where energy and services can be exchanged.* This is a fundamental change from traditional BPM structure and operational models but is necessitated by changes happening at the distribution level. A significant and useful consequence of this model is that the transmission system operator does not need information on state or assets connected at the distribution level – *only information about state and agreement on energy and services exchanges at the transmission/distribution interface*. This relieves the transmission system operator of the massive burden of receiving telemetry and issuing dispatches to potentially millions of edge-connected devices and of needing to understand (have observability of) distribution grid state. It further resolves the issue of potential collisions over distribution reliability responsibility vs. tier-bypassing and hidden coupling-

[10] P De Martini and L Kristov, Distribution Systems In A High Distributed Energy Resources Future, LBNL Report No. 2, Future Electric Utility Regulation series, October 2015. Available online: https://gridarchitecture.pnnl.gov/media/advanced/FEUR_2%20distribution%20systems%2020151022.pdf

induced reliability problems. This structure thereby benefits both the transmission system operator and the distribution operator.

This industry structure introduces a new interface: the DSO/TSO interface (indicated by the red double ended arrow in Figure 1). This interface is not the same as the system planning interface; it is operational in nature and may also include market functions if DER will participate in organized wholesale markets. This interface must support real time operations on the same time scales as the bulk transmission generators and the TSO do. In this regard, this industry structure changes the TSO view of the distribution system from a passive aggregated load to a combination of load and power/energy resource. The T/D physical (electrical) interface becomes a combination of load aggregation point and generation tie point. The information flows across this interface include:

- Forecasts (load, available DER)
- Bids and clearings
- Dispatch/curtail requests
- Aggregated distribution grid state, including grid services capacities
- Grid services requests
- Measurement and validation data

This structure limits the number of new interfaces seen by the TSO to the number of distribution systems it serves, as opposed to the (potentially very much larger) number of DERs and ESOs that may want to participate in grid operations. This helps with scalability at the TSO level and limits the number of communication paths that the TSO must guard. Also, these paths have electric utilities at both ends, as opposed to unregulated third parties on one end.

A consequence of this structure is that DER telemetry flows and dispatch instruction flows have a structure shown in Figure 2, where the lines indicate bidirectional data flow paths.[11]

[11] JD Taft, DER Telemetry Communication Architecture for ESOs, DSOs, and System Operators, PNNL-27057, November, 2017. Available online: https://gridarchitecture.pnnl.gov/media/advanced/DER_Communication_Structure_final_GMLC.pdf

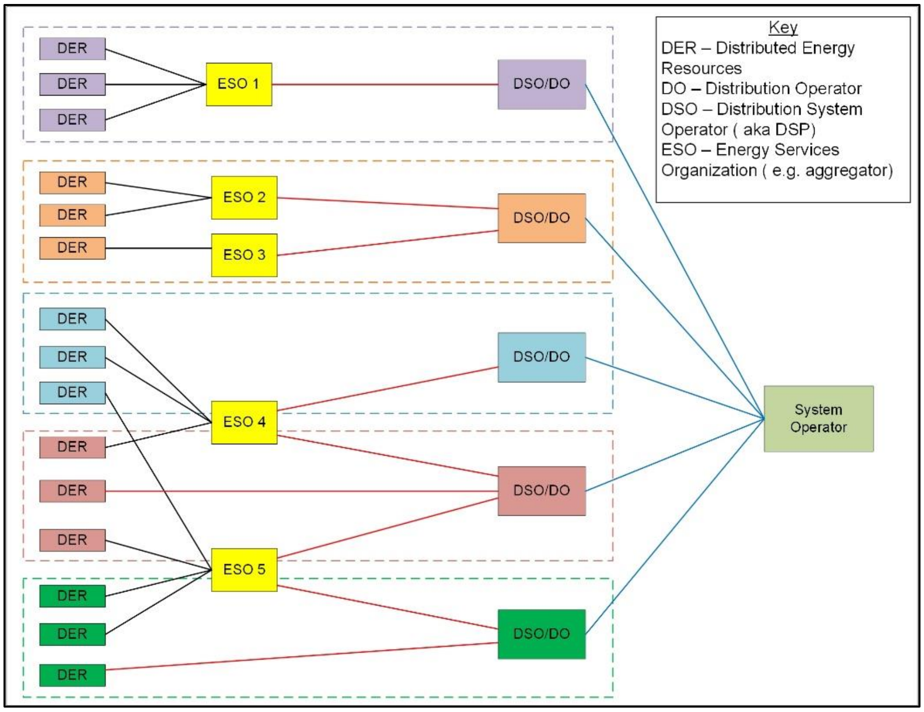

Figure 2 Multi-DSO DER Telemetry Flows

Note that no tier bypassing occurs in this structure. Also note that one TSO may deal with many DSOs (one for each distribution system that is connected to the TSO's transmission systems), and each DSO may deal with many Energy Services Organizations (ESOs – DER aggregators, remote building energy managers, etc.). ESOs may well operate in multiple distribution service areas and so may deal with multiple DSOs and may interpenetrate each other's "market territories" in a given distribution service area. The number of DSOs is equal to the number of distribution systems involved. The number of ESOs is arbitrary.

In this structure, the distribution systems are essentially clouds from the point of view of the TSO. This means that the TSO does not need state information or telemetry from inside each distribution cloud. The TSO needs visibility at the TSO/DSO interface for the agreed-upon exchange of energy and services at that interface. The DSO provides the necessary state information to the TSO, just as a bulk generator does and it accepts dispatch requests from the TSO in the same manner. As Figure 3 illustrates, what lies inside each distribution cloud is not visible to the TSO. The DSO has the responsibility to manage assets inside the cloud to meet the agreement at the T/D interface, which can include not just energy, but also grid services and resilience support.

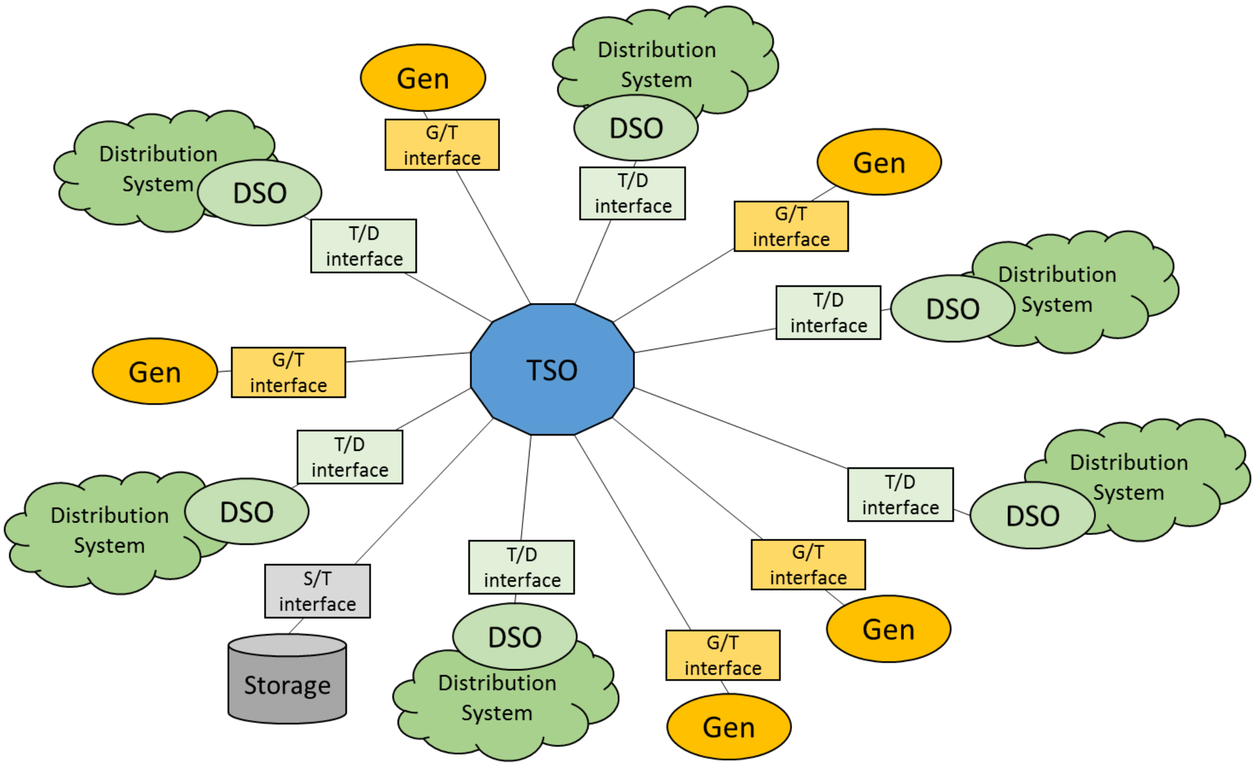

Figure 3 Distribution Systems as Clouds Behind DSOs from the TSO View Point

Specification 1 details:

1.1 The TSO treats the T/D connection as a combination of load point and generation tie. It arranges agreement with the DSO on energy and services to be exchanged at the T/D Interface. The TSO has responsibility for system balance and interchange with neighboring bulk power systems. It may also operate wholesale bulk electricity markets.

1.2 The TSO limits its grid observability to the bulk power system up to the T/D interface; it does not obtain grid state or operational data from DER devices or aggregators. As far as the TSO is concerned, a distribution system is a cloud into which the TSO does not have visibility.

1.3 Distribution providers have a total Distribution System Operator role. The DSO is responsible for managing distribution assets to meet an agreement with the TSO as to power and energy flows at the transmission/distribution interface substations.

1.4 The DSO is responsible for managing DER and power flows to/from and inside its distribution service area to maintain distribution reliability and meets its responsibilities to the TSO at the T/D interface, including power and energy flows across that interface, and management of volatility arising from distribution connected elements.

Specification 2: Electric Circuit Structures

2.1 Variable Topological Structure

At the transmission level, circuit segmentation occurs at the substations and switching stations, with switchgear as the connecting elements. Control of structure is performed via SCADA-based control. This form of variable grid structure is well established and will not be further detailed here. It is worth recalling however, that variable grid structure is a multi-scale concept. Transmission/distribution interface substations are points where, from a transmission level point of view, connections exist to whole distribution system service areas, which at the transmission level can be viewed as single components attached to the transmission grid. The switchgear in a substation or switching station is the mechanism by which grid structure can be modified – by connecting or disconnecting whole distribution system service areas, for example, or switching transmission lines in or out of the system. At the level of the distribution system, the grid segment concept applies again in a recursive manner. Figure 4 illustrates a multi-scale view of grid segment structure.

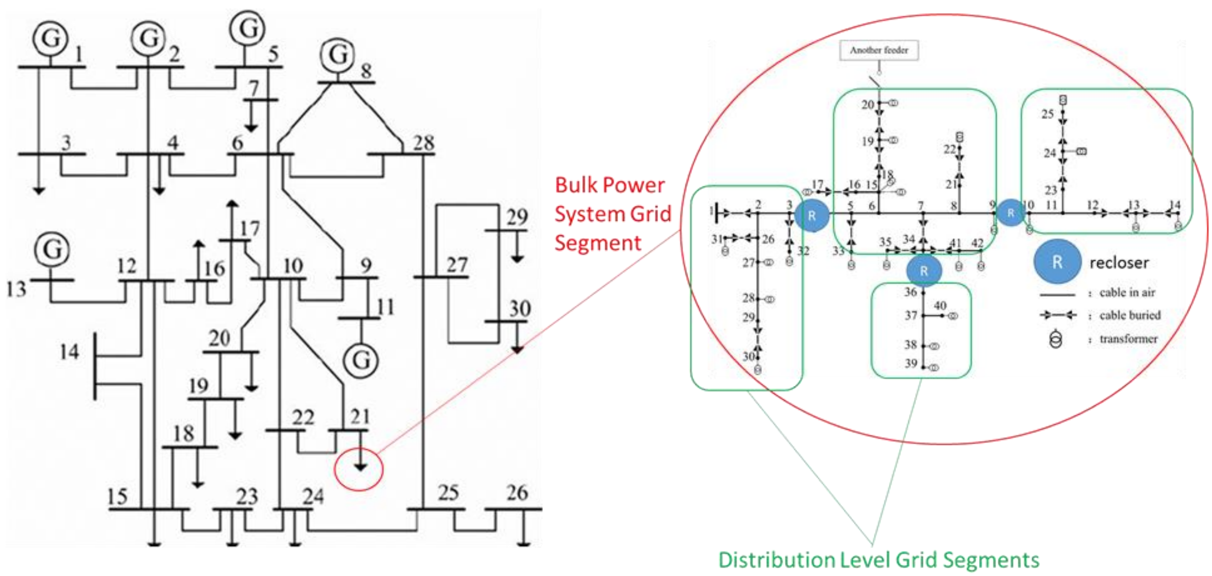

Figure 4 Multi-Layer View of Grid Segmentation

Variable structure refers to changes in circuit topology based on the switching of connecting elements (primarily switchgear at the transmission level).

For more details on variable grid structure, see the Variable Grid Structure Reference Architecture.[12]

[12] GMLC Architecture Team, Architectural Framework for Variable Structure Grids, September 2019, available online: https://gridarchitecture.pnnl.gov/library.aspx

2.2 Grid Internal Flow Control

The typical view of a Bulk Power System as seen by a Transmission System Operator is illustrated by Figure 5. The set of injections (generators and storage units providing energy), the set of loads (T/D interconnections and storage taking energy for the grid) and the points of interchange with other bulk power systems constitutes a set of external power flows. The flows across the transmission grid constitute a set of internal power flows (internal to the transmission grid).

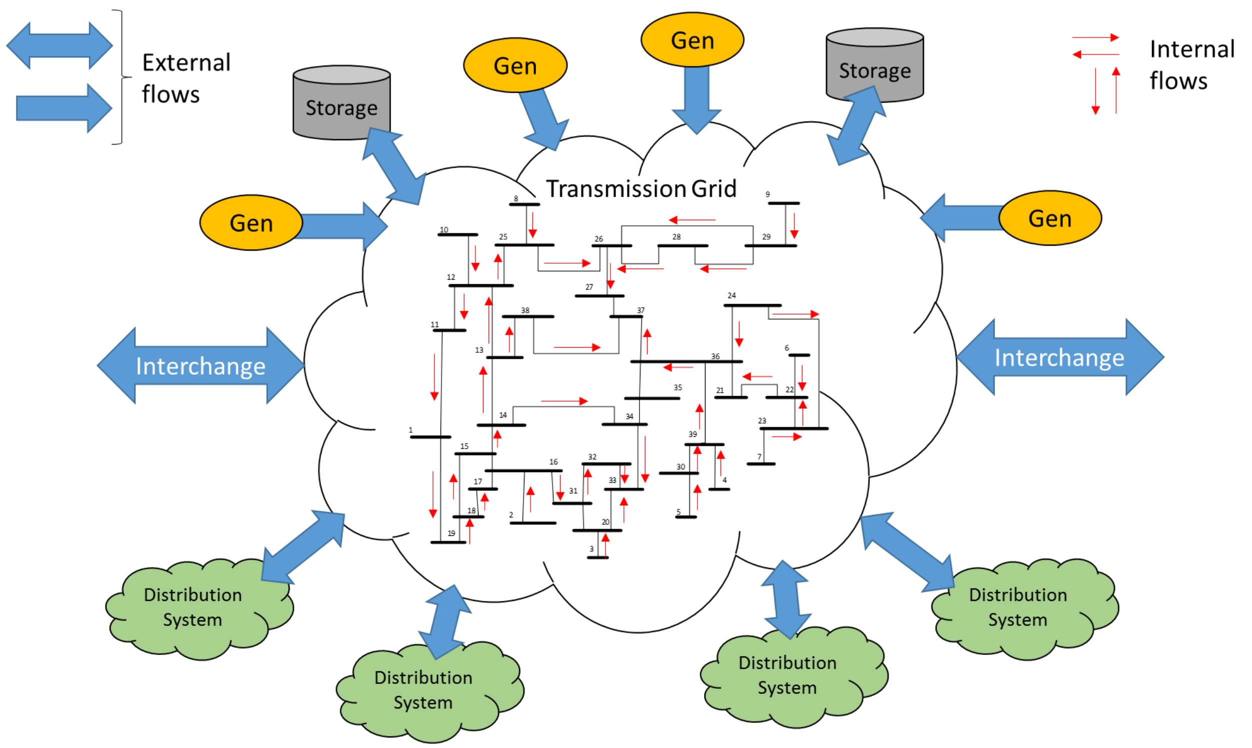

Figure 5 External and Internal BPS Power Flows

Various means exist to deal with the external power flows but here we are concerned with flows internal to the transmission grid.

Traditionally, internal power flows have been determined by the system model (essentially the admittance matrix) and the external flows. The system model has been taken as fixed for a given topology but with the emergence of new technologies based on power electronics, it has become feasible to provide the means to have adjustable (controllable) branch admittances. Consequently, new degrees of freedom can be introduced for internal flow control, thus impacting transmission line utilization and congestion.

Figure 6 shows a transmission grid with a set of power flow controllers (PFCs) on various branches. Short of placing flow control devices on all branches (likely to be deemed too expensive and not necessary), there is no obvious architectural principle to guide the allocation of these devices on a transmission grid, so their locations would be determined via engineering analysis and design. From an architectural standpoint, the incorporation of internal power flow control with structure control converts a static transmission grid into a dynamic transmission structure that with the appropriate control, provides for extended operational flexibility and therefore resilience and operational efficiency.

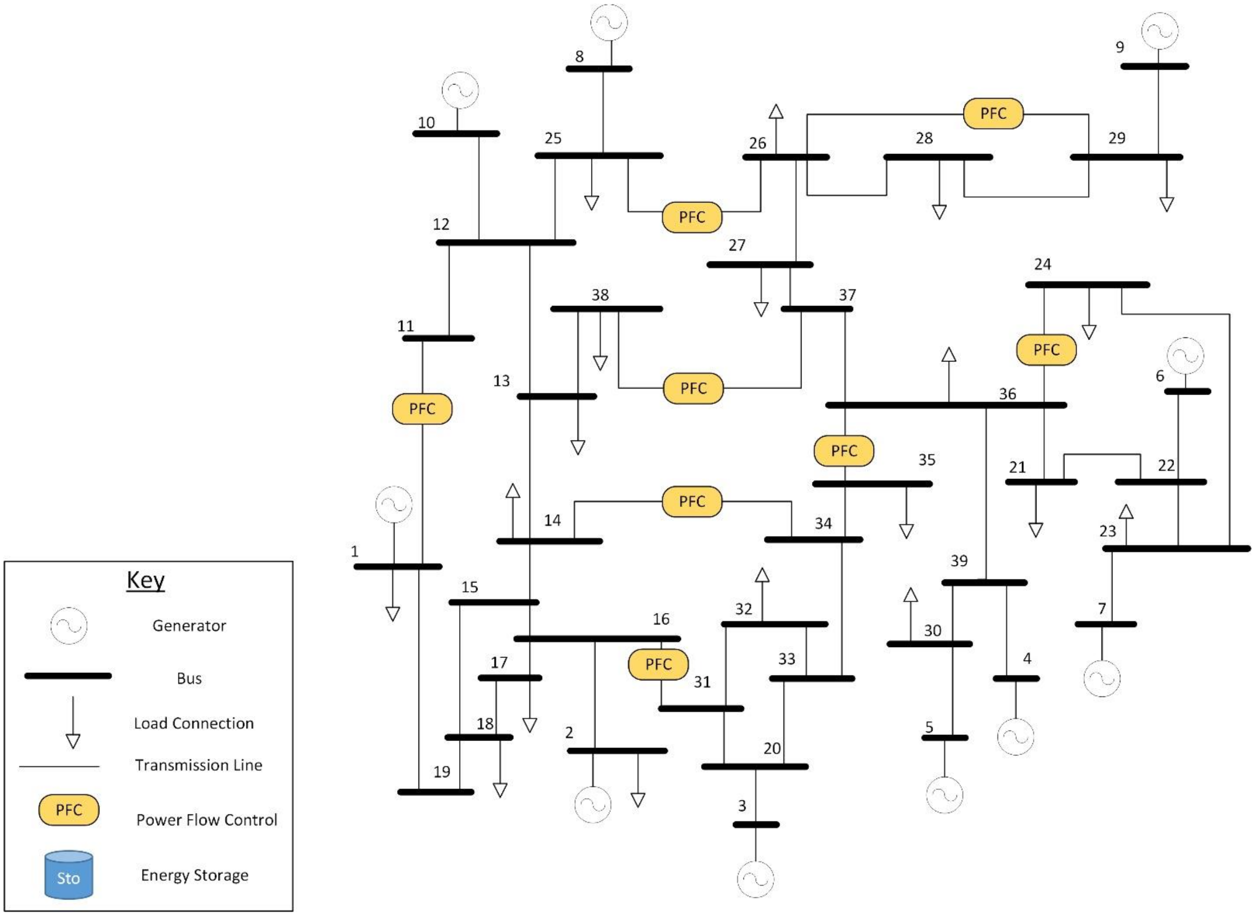

Figure 6 Example Grid with Internal Power Flow Controllers

2.3 Stabilization

Power electronics devices (generally known as FACTS) are already well known as means to perform various kinds of stabilization for bulk power systems. In addition, power system stabilizers are in common use, as are synchronous condensers. As the mix of generation shifts from high rotational inertia turbines to low inertia systems like solar PV and wind generation, system inertia will decrease and this has led to a concern about decreasing inherent stability of the grid. One of the proposed solutions is to use bulk energy storage with appropriate controls to augment inherent grid inertia with “synthetic” or “pseudo” inertia.[13] See Specification 6 for more information about energy storage in bulk power systems.

[13] It has also been suggested that wind turbines, solar PV, and other resources could be applied to this problem.

Operation of devices to generate negative synthetic inertia could be used to increase system agility.

Specification 2 details:

2.1 Use power flow control internally in transmission systems to provide new degrees of freedom in managing power flow and congestion.

2.2 At low penetrations, PFCs can be operated independently. At large penetrations, operate them as a network of devices, and the power flow solution must simultaneously solve for grid structure, grid internal parameters (PFC settings) and flow.

2.3 When using storage or other means to augment inherent grid inertia, operated the devices as a coordinated network, not as a loose collection of independent service devices. Preserve the capability to use the devices for negative as well as positive inertia.

Specification 3: Wide Area Synchronized Sensing and Communications Layer

3.1 Sensing and Communication Layer/Platform

The layering and platform concepts are applied to electric infrastructure, sensing and measurement, and communications for electric distribution to define a platform for flexible electric distribution operations. Layering and consequent decoupling of applications enhances configurability, functional flexibility, and functional extensibility.[14]

Note that the sensing and communications structure is static in the same sense as the physical circuit layer (electric hardware components). Consequently, the circuit hardware and the sensing/communications layer can be treated together as a platform.[15]

Sensing and communications are associated with the base electric circuit hardware. This means that the physical sensing and communications layer is also static for purposes of variable grid structure.

Sensing and measurement and communications for transmission systems can be combined into an observability platform. This is especially true for PMU networks. By using the capabilities of modern communications networks, the combination of sensing devices and communications can form an infrastructure layer that acts as an observability platform (Core Resilience Architecture principle 3.2).

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[14] J Taft and P De Martini, Sensing and Measurement Architecture for Grid Modernization, PNNL-25249, Feb 2016. Available online: https://gridarchitecture.pnnl.gov/media/advanced/Sensor%20Networks%20for%20Electric%20Power%20Systems.pdf

[15] A platform is a stable collection of components that provide fundamental or commonly-needed capabilities and services to a variable set of uses or applications through well-defined interfaces.

Application of the core-edge network architecture structure and proper allocation of functions to avoid introducing structural constraints (such as with phasor data concentrator stacking) leads to a distributed platform structure. Figure 7 illustrates the platform for private communication networks.

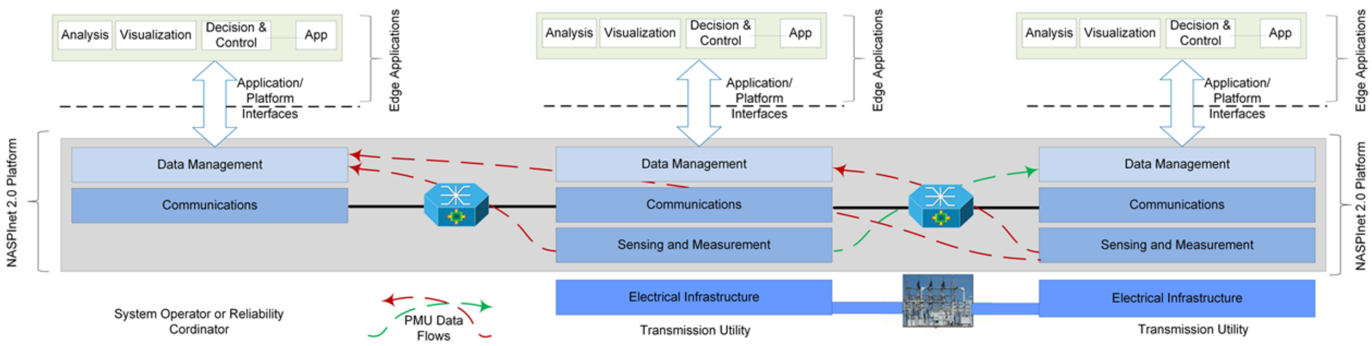

Figure 7 Transmission Observability Platform with Private Networks

Figure 8 illustrates the platform using telecommunications service provider networks. In this case, a combination of communications networks, some parts owned by the electric utilities and some by third parties, are combined to provide the wide area transport of transmission grid sensor data.

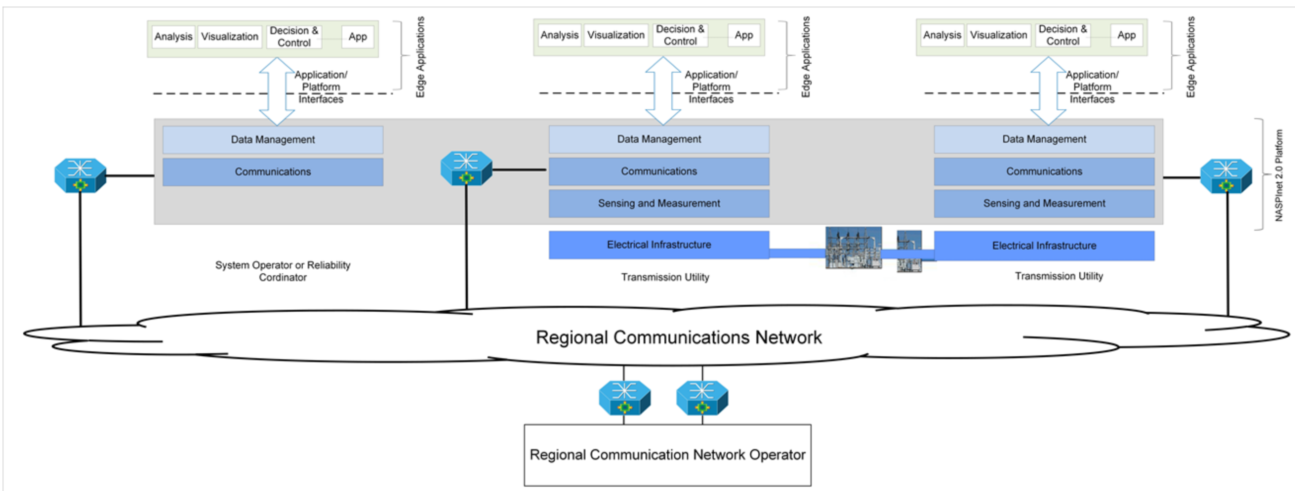

Figure 8 Transmission Observability Platform with Telecommunications Service Provider Networks

The same communication network core-edge principle applies as with the private network version, as do the other guidelines in the NASPInet 2.0 guidance.[16]

[16] NASPI, NASPInet 2.0 Architecture Guidance, October 2019, available online: https://gridarchitecture.pnnl.gov/media/NASPInet%202%20v1.19_PNNL.pdf

Specification 3.1 details:

3.1.1 Treat sensing and communications network layer as a static structure associated with the static physical as-built electric circuit structure.

3.1.2 Make the communications network a full services IP network. In particular, provide streaming protocols (MPLS and PIM/SSM, STTP, etc.) so that the network can function as a distributed, access-controlled publish/subscribe mechanism.

3.1.3 Provide a set of functions and services for network, sensor, data, and security management as part of this layer.

3.1.4 Combine the sensing, communications layer, and applications to form a distributed

3.2 Timing Distribution Redundancy

Synchrophasors and other elements of grid measurement and control require timing distribution or another mean of establishing synchronism (agreement among the elements of the present time or time stamp value). The typical solution for this has been to use Global Positioning System (GPS) timing signals but this is recognized as being weak from a resilience standpoint. While timing may be derived from multiple satellites, the GPS system still represents a potential single point of failure, especially in the event of RF interference, space weather problems or cyber-attack.[17] Consequently, additional sources and methods of synchronization are desirable in line with the NASPInet 2.0 architecture principles.[18] In Figure 9, the middle illustration shows a structure in which GPS timing is combined with two other sources (Cesium clock and Loran) whose timing signals are distributed through the NASPInet communication network.

[17] M S Almas, et. al., Vulnerability of Phasor-Based WAMPAC Applications to Time Synchronizing Spoofing, available on IEEE Xplore. See also https://www.naspi.org/sites/.../04_Vanfretti_VulnerablitlyWAMPAC_20180425.pdf

[18] NASPI Time Synchronization task Force, Time Synchronization in the Electric Power System, NASPI-2017-TR-001, March 30, 2017, available online: https://www.naspi.org/node/608

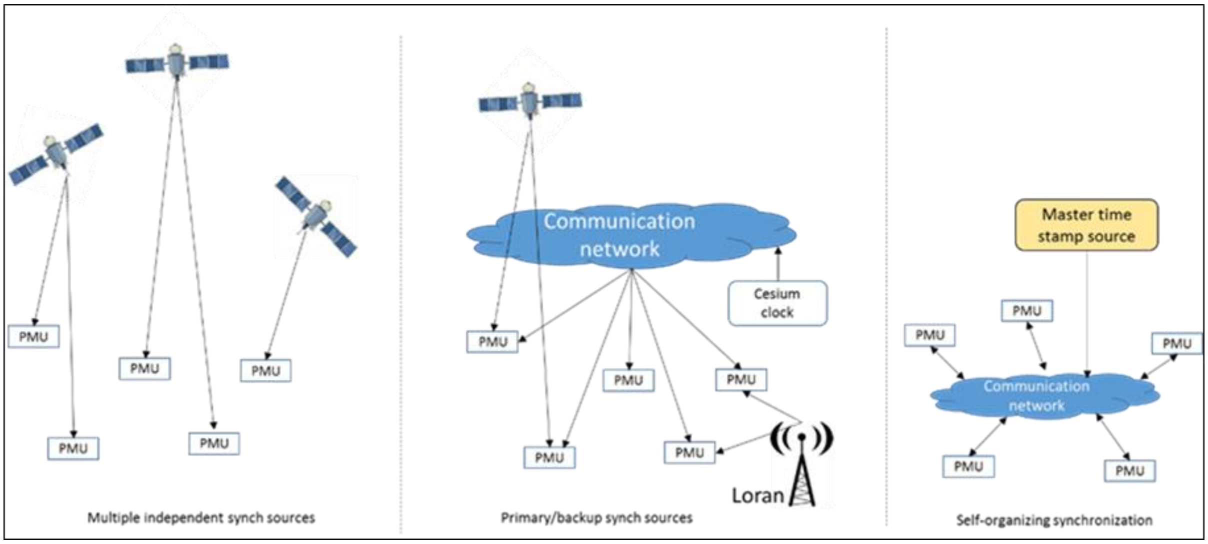

Figure 9 Network Timing Sources

Alternatively, a sensor network such as a PMU network may be self-synchronizing[19] such that sampling temporal alignment is achieved internally in the network and then external sources are only needed to inject information for time/date stamping into the network as a whole, rather than at each sampling point. Such an arrangement requires that the measurement and control devices to be synchronized be able to communicate with each other, including across organization boundaries in the case of transmission-level PMU networks.

The field of Wireless Sensor Networks has led to the development of time sync methods tailored to the needs of low power devices. PMUs do not fit that description and these approaches have not been given much consideration for them.[20,21,22]

Figure 10 illustrates a multi-organization network architecture for network-based timing distribution.

[19] G. Brandner, et al., "Firefly Synchronization with Phase Rate Equalization and Its Experimental Analysis in Wireless Systems," Elsevier Computer Networks 97, June 24, 2016, pp. 74-87.
[20] R V Bhapkar, Consensus in Large Scale Wireless Sensor Actuator Networks: Time Synchronization as a case study, University of West Virginia, 2013, available online: https://pdfs.semanticscholar.org/d494/e69330a0987b5b2cf9e3e5e1e92d70a7f100.pdf
[21] S Ganeriwal, et al., Timing-sync Protocol for Sensor Networks, Sensys 03, 2003, available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.58.3367&rep=rep1&type=pdf
[22] M Maroti, et al., The Flooding Time Synchronization Protocol, Vanderbilt University, 2004, available online: https://dl.acm.org/citation.cfm?id=1031495.1031501

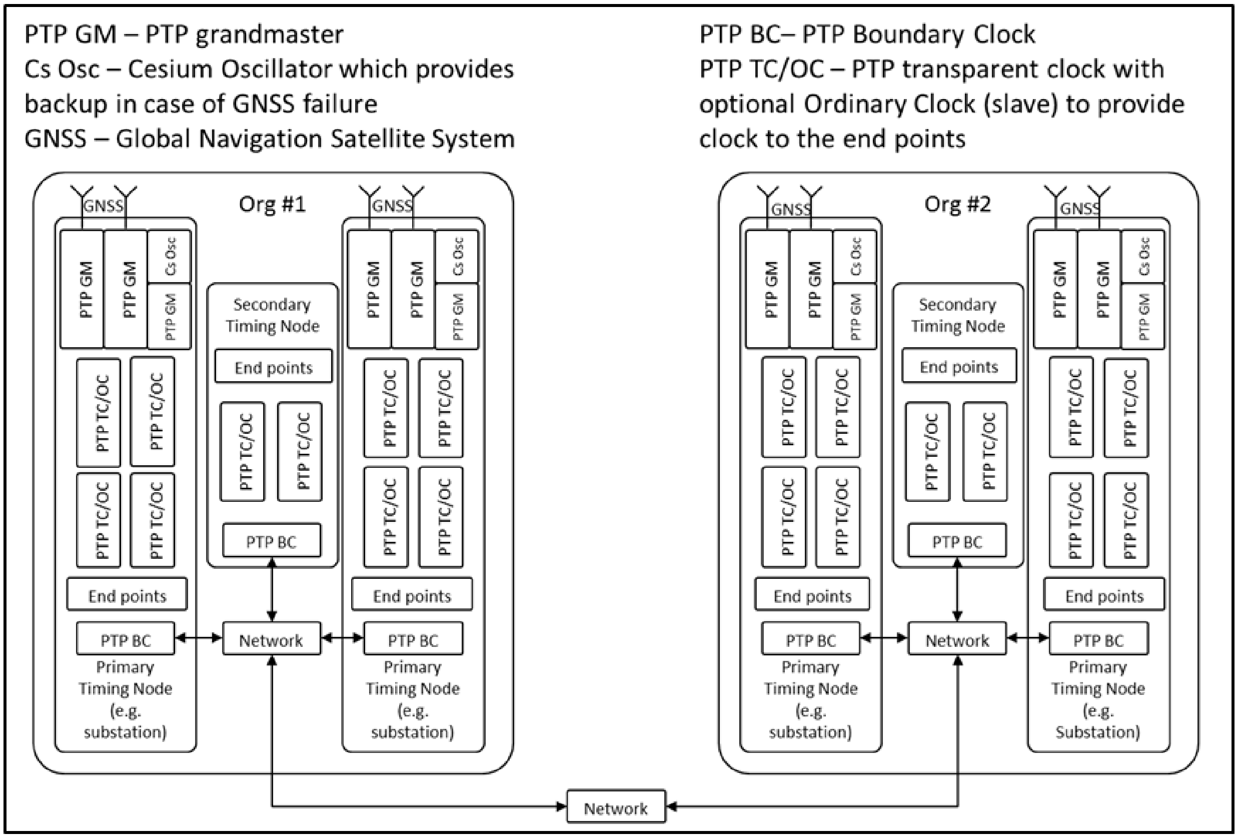

Figure 10 Wide Area Timing Distribution Architecture

Specification 3.2 details:

3.2.1 Provide time distribution at every hop in the network.

3.2.2 Use transparent Clocks (TCs) at every node as per C37.238.

3.2.2.1 This clock measures delay over the node and inserts the information into the correction field in
order to compensate for the variations in the propagation delay

3.2.2.2 Use TCs to allow additional slave clocks into the node in order to bring accurate timing to this node.

3.2.3 Monitor the integrity of the GPS reference, and switch to an alternate source if compromised.

3.2.4 Use redundant primary sources of time such as military grade multi-standard Global Navigation Satellite System (GPS/GLONASS/Galileo) at key points and recovery logic for use of timing sources.

3.2.5 Use boundary clocks (BCs) where the networks of different organizations connect.

3.2.5.1 BC on the sending side indicates what time is sent to the receiving organization.

3.2.5.2 BC on the receiving site terminates the time and indicates what it receives.

3.2.5.3 Receiving BC distributes time further in own organization.

3.2.6 Use an atomic clock as a backup source for GPS. With 1E-11 accuracy, the commercial Cesium clock can maintain 1 millisecond (1E-3) accuracy for 1E8 seconds or about 1,157 days (3.17 years). If 1 microsecond accuracy is required between different systems then accuracy can be kept by the atomic clock for 27.77 hours, assuming initial time offset of 0.

3.3 Transmission Substation Networks

In addition to regional communications, substations contain internal communication networks. A wide variety of topologies are available for such networks, with an array of advantages and disadvantages. Given that any grid which does not operate in a completely decentralized manner must depend heavily on communications, it is appropriate to consider more than the bare minimum for intra-substation network structure.

Substation networks for critical infrastructure in a high resilience architecture use the redundant tree topology of Figure 11. A variety of network topologies are available for substations and less critical substations may use less resilient approaches.[23] The topology shown here provides high redundancy and low latency and with proper protocol choices can greatly limit the impact of network faults and provide very high availability (six+ nines).[24] The cited document also provides topology comparisons and comparison of IEC 61850 over Ethernet vs. IEC 61805 over UDP/TCP over IPv4/v6.

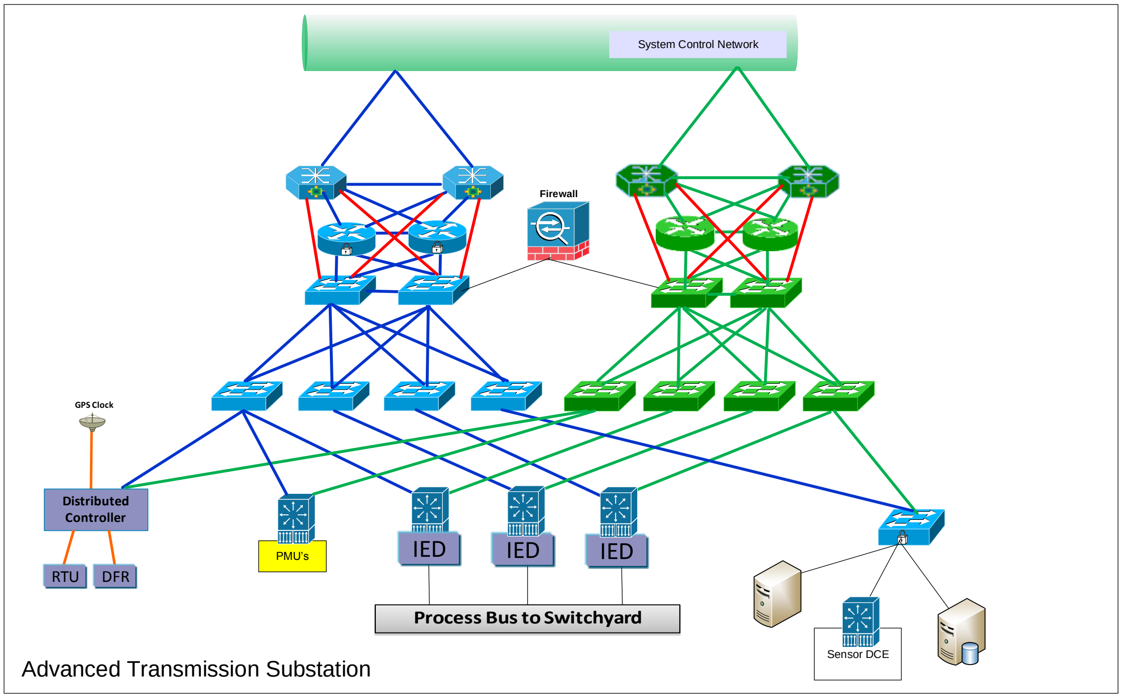

Figure 11 High Resilience Substation Communication Network

3.3 Specification details:

3.3.1 Use meshed two-tier dual tree network topology.

3.3.2 Provide dual connections to the WAN(s).

3.3.3 Attach network services to the upper tier of the dual tree structure.

3.3.4 Substation sensors and other internal communicating devices connect to both trees of the substation network.

3.3.5 Use full meshing for the upper tier of each tree

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[23] For a full discussion of network topology alternatives for substations and their relative merits, see the Cisco Substation Design and Implementation Guide, available on request from Cisco Systems, Inc.
[24] N. Yadav and E. Kapadia, Substation of the Future: Improve Network Reliability and Protocol Interaction, Grid Interop, December 2010.

3.4 Control/Operations/Data Center Network Structure

Path redundancy is key to both resilience and low latency for operations and data center internal networks. The structure of Figure 12 provides for efficient and redundant connection of telemetry data flows into the center, with provision for real time flow to applications, as well as data flow to/from a storage sub-network.

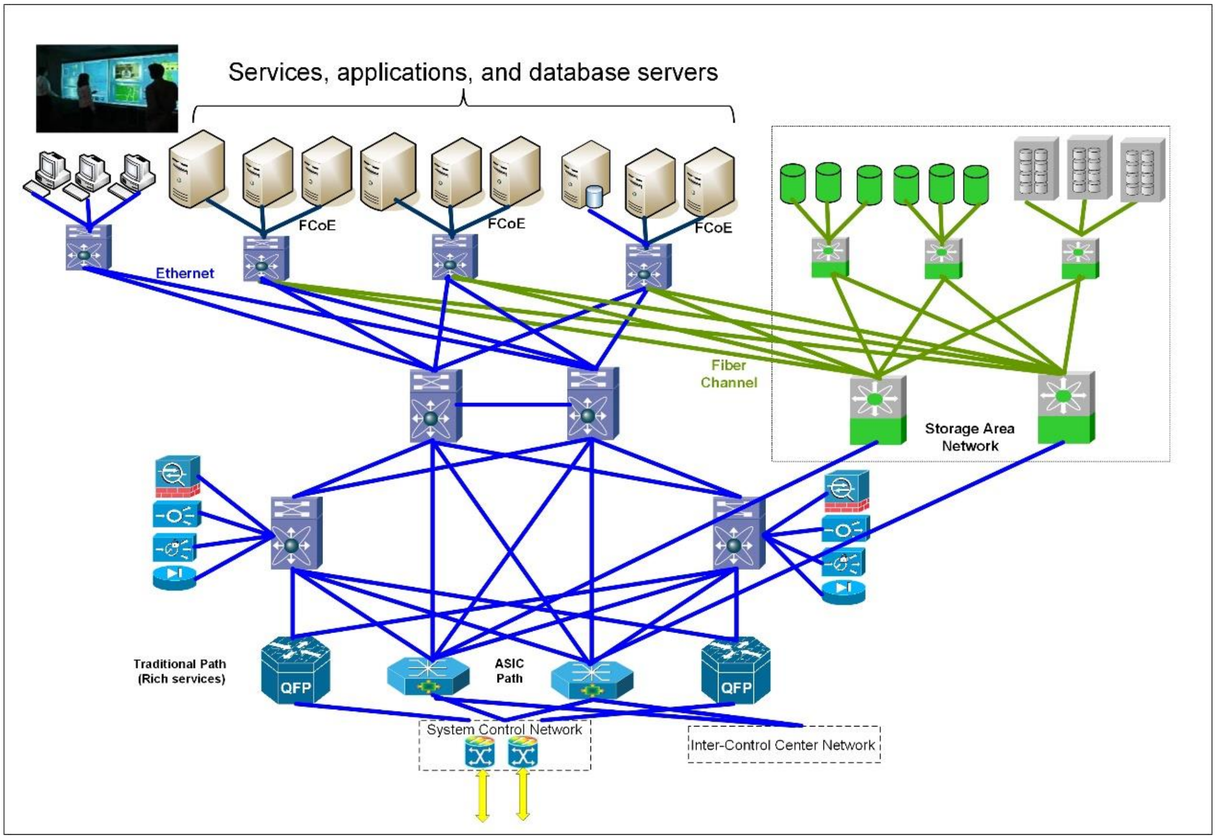

Figure 12 High Resilience Control Center Communications Network

When telecommunications service providers are used for wide area communications, the dual service provider model with redundant paths as shown in Figure 13 avoids the single point of failure problem (in this case outage of a service provider). Note the dual redundant connections on each end.

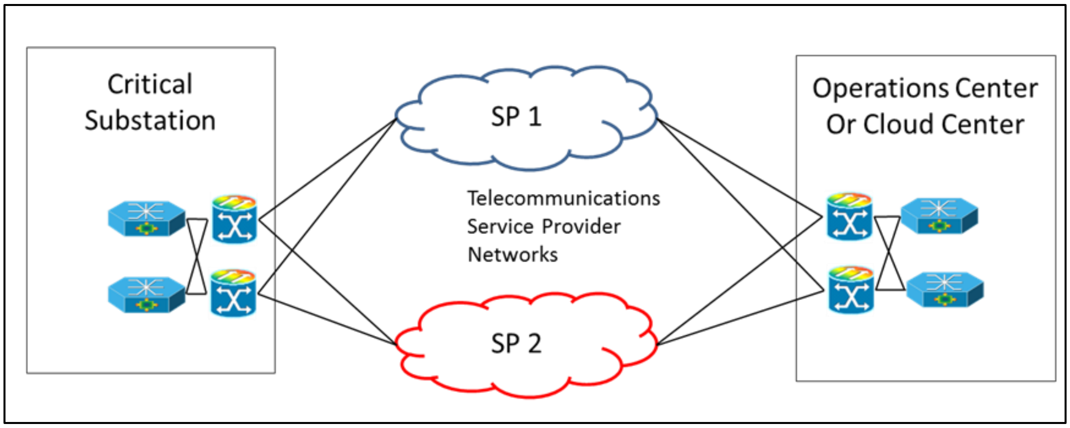

Figure 13 Redundant Telecommunications Service Provider Communications Structure

3.4 Specification details:

3.4.1 Use mesh multi-path topology.

3.4.2 Provide dual redundant connections to the WAN(s).

3.4.3 Provide both rich services paths and low latency paths from the WAN connections to the applications and data base servers.

3.4.4 Attach network services servers to the multi-path mesh.

3.4.5 Use two telecommunications service providers to connect operations centers and critical substations for path redundancy and single point of failure avoidance.

Specification 4: Redundant Closed Loop Backup Protection

Backup protection for transmission systems requires digital communications between substations and one or more transmission operations centers. Simple hub-and-spoke network structure is not sufficiently resilient, so the combination of dual redundant telecommunications networks and dual hub-and-spoke structure improve resilience by avoiding single points of failure and providing redundant paths for data flow. Figure 14 illustrates the basic structure.

In addition to the redundancy aspects of this structure, it also has the capability to support closed loop functionality. The advantages of this approach include:[25]

[25] E Udren, Synchrophasor- Based Wide- Area Backup Protection System, i- PCGRID Conference San Francisco, CA March 2019, available online: https://ipcgrid.ece.msstate.edu/presentations/2019/Eric%20Udren%20-

- Faster, precise backup - disconnects exactly what is needed –no more.
- Immune to high penetration of inverter & low-current generation sources.
- Ignores loads and swings.
- Use voltage phasors for selective unstable-swing trip or block).
- No coordination studies or core application settings.
- Relaxed coordination work for slower Zone 2/3 distance
- Reduces compliance issues for PRC-023, PRC-026, PRC-027
- Complete self-monitoring - no hidden failures; no maintenance tests – 24/7 operational state awareness

%20Synchrophasor-based%20Wide%20Area%20Backup%20Protection%20System%20-%20iPCGRID%202019.pdf

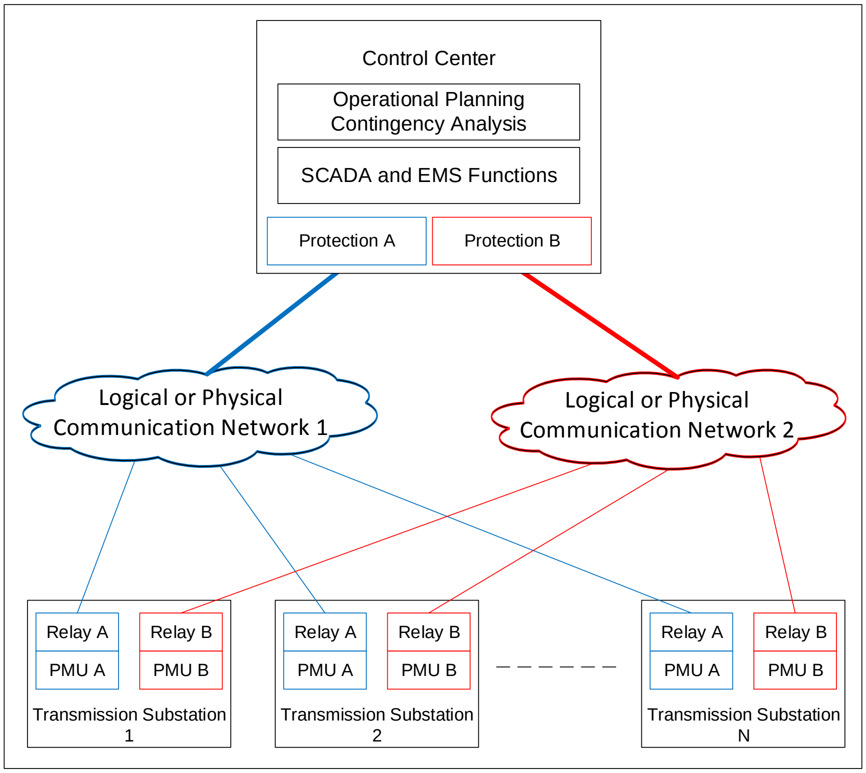

Figure 14 Backup Protection Redundant Structure

Specification 4 details:

4.1 Use at least two separate communications networks for backup protection data flows between substations and control centers.

4.2 Use dual hub-and-spoke (or its equivalent if more than two networks are involved) to connect substations to communications networks.

4.3 Use dual redundant relays and PMUs in the substations.

4.4 Use separate redundant relay logic (Protection A and Protection B) at the control center.

Specification 5: Buffering and Bulk Energy Storage

Buffering in Complex Systems

Buffers are mechanisms for decoupling flow variations, especially random or unpredictable variations. The presence of a buffer provides a system with "springiness" or "sponginess" that makes it resilient to a variety of perturbations. In fact, lack of such springiness is a resilience vulnerability.

Most complex systems have some form of buffering. Communication systems have "jitter buffers" to even out the flow of data bits in communication network transmission. Computing systems have various kinds of data buffers that operate on differing time scales.[26] Logistics systems have buffers – they are called warehouses. Water and gas systems have buffers – they are called storage tanks. In each case, the buffer is some form of storage that evens out irregular flows, thus reducing or eliminating the impact of volatility (fluctuation or interruption) in source or use.

Grid energy storage receives energy in the form of electricity from the power grid and then later either returns it to the grid as electricity ("reflexive") or converts it to some other use ("transitive") as Figure 15 illustrates.

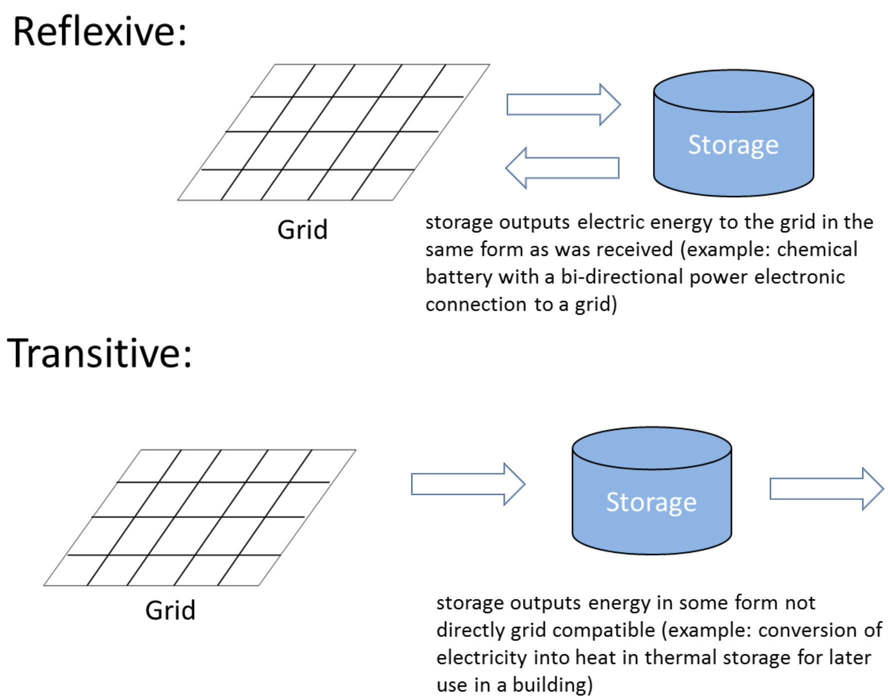

Figure 15 Storage Process Models

The use of storage as a grid operational tool will focus on reflexive storage that can operate on fast (short) time scales with considerable functional flexibility. This leads to the concept model for grid energy storage shown in Figure 16, which has three major elements: the energy storage device, advanced controls,[27] and a flexible grid interface. Note that while it would not be unusual to consider electrochemical batteries for the storage elements, implementations based on other technologies are possible. The reason for the power electronics element is that while the electric power grid uses

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[26] Some data may persist only for only very short periods of times and be stored in small volatile memory buffers, whereas other data may persist for years and be stored in non-volatile databases.

[27] Advanced storage control is multi-modal, so that the storage device can be used in a number of ways and the operating mode can be changed very quickly and automatically to meet changing grid conditions.

alternating current (AC) most storage elements operate with direct current (DC). Power electronics provides the means to connect DC and AC systems and also offers much flexibility in terms of actual control functions. Real storage devices also have storage management systems, communications interfaces and other components, but the three elements shown in the diagram are the basis for grid energy storage that can be used as a general purpose grid element.

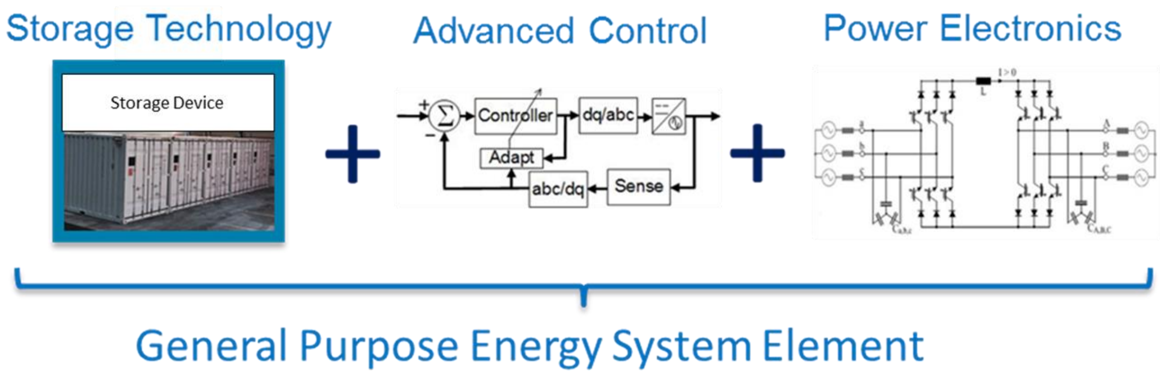

Figure 16 General Purpose Grid Element

In recent years, it has been the practice to treat grid storage as an attached (not embedded) ancillary device capable of supplying many different services to the grid.[28] This has led to the paradigm of "stacking" services, meaning supplying multiple services with the same storage device, perhaps even to different service consumers. Such capability has been treated as either something to be bid into wholesale electricity markets (where they exist), or as something to be analyzed via Benefit/Cost Analysis (BCA) to justify investment.

Another way to use of grid storage is to embed it in the grid as core infrastructure for the purposes of improving operating characteristics and grid resilience. In this approach, storage is integrated into in the grid (such as at substations) as opposed to being merely attached, and while it may or may not be owned by the electric utility, it is certainly controlled directly by the electric utility. In this model, storage is not used by the electric utilities to bid services into electricity markets. It is used for operational flexibility.

Embedded Storage Allocation

Allocation is both an architectural and an engineering issue. At the architectural stage, component allocation (how components are connected) is a key structural consideration and storage is considered to be a black box component. At the engineering stage, a great many detailed considerations come into play that are not discussed here. At the transmission level, there are three primary allocation strategies:

[28] P Balducci, et al., The Salem Smart Power Center, PNNL-26858, Sept. 2017, available online: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26858.pdf

1. Locate the storage devices in load connection points (transmission/distribution substations), or in substations only one link removed from such points. Do not locate storage on the same bus as a generator. Figure 17 illustrates such a strategy.
2. Locate storage only on buses that are not load connection points. Keep storage that is located on the same bus as a generator to a minumum. Figure 18 illustrates this strategy on the same transmission system as with strategy 1.
3. Locate storage only on buses that have generators attached. See Figure 19.

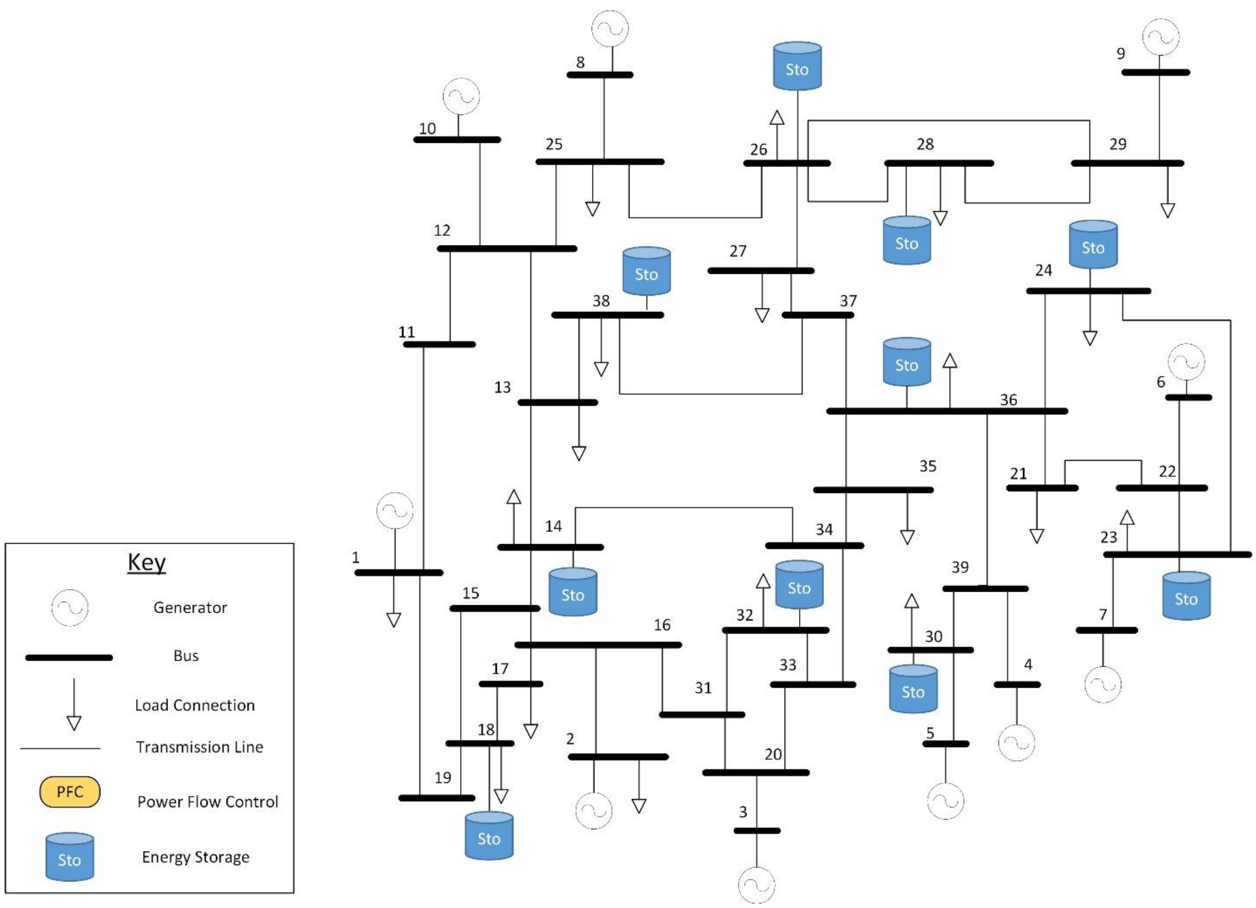

Figure 17 Storage on T/D Interface Buses

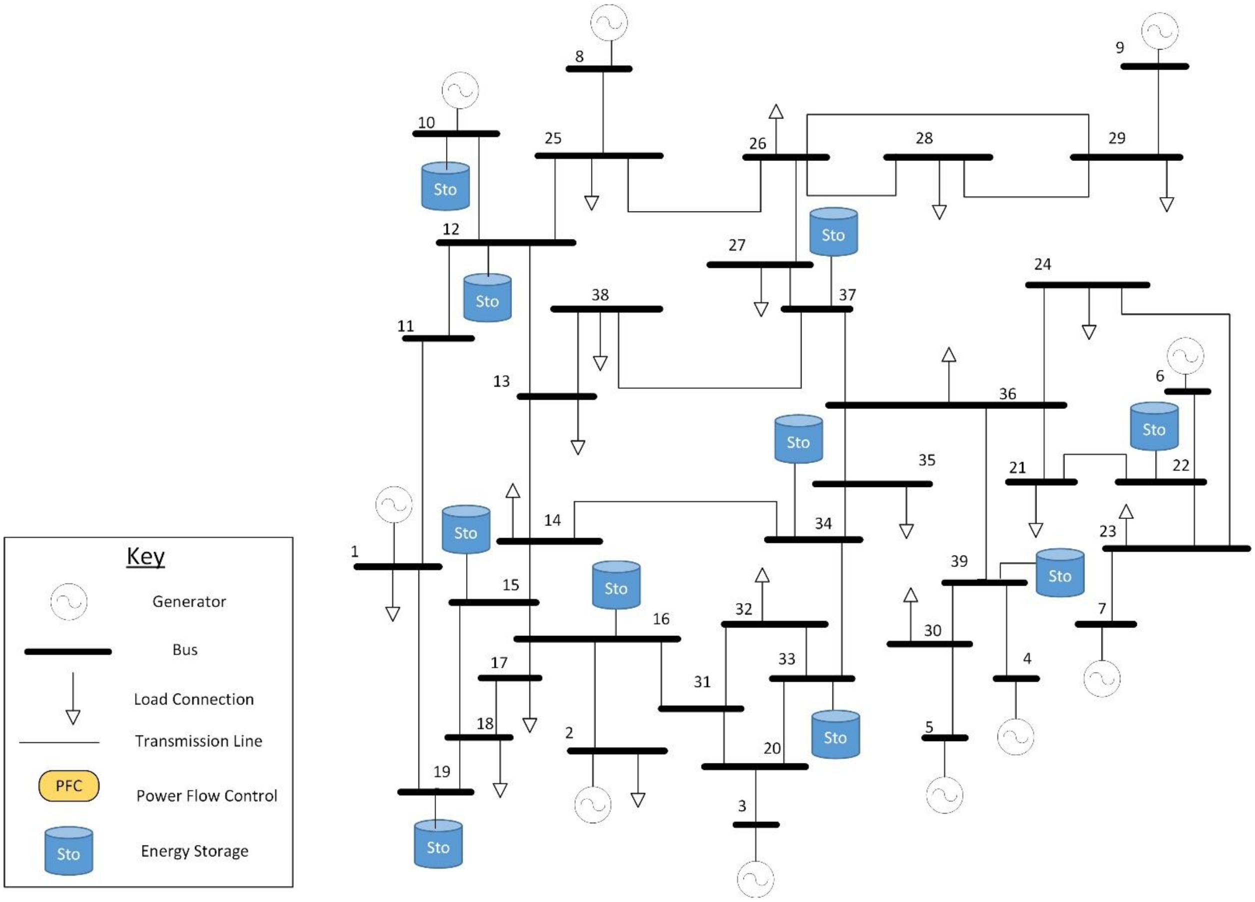

Figure 18 Storage on Transmission-Only Buses

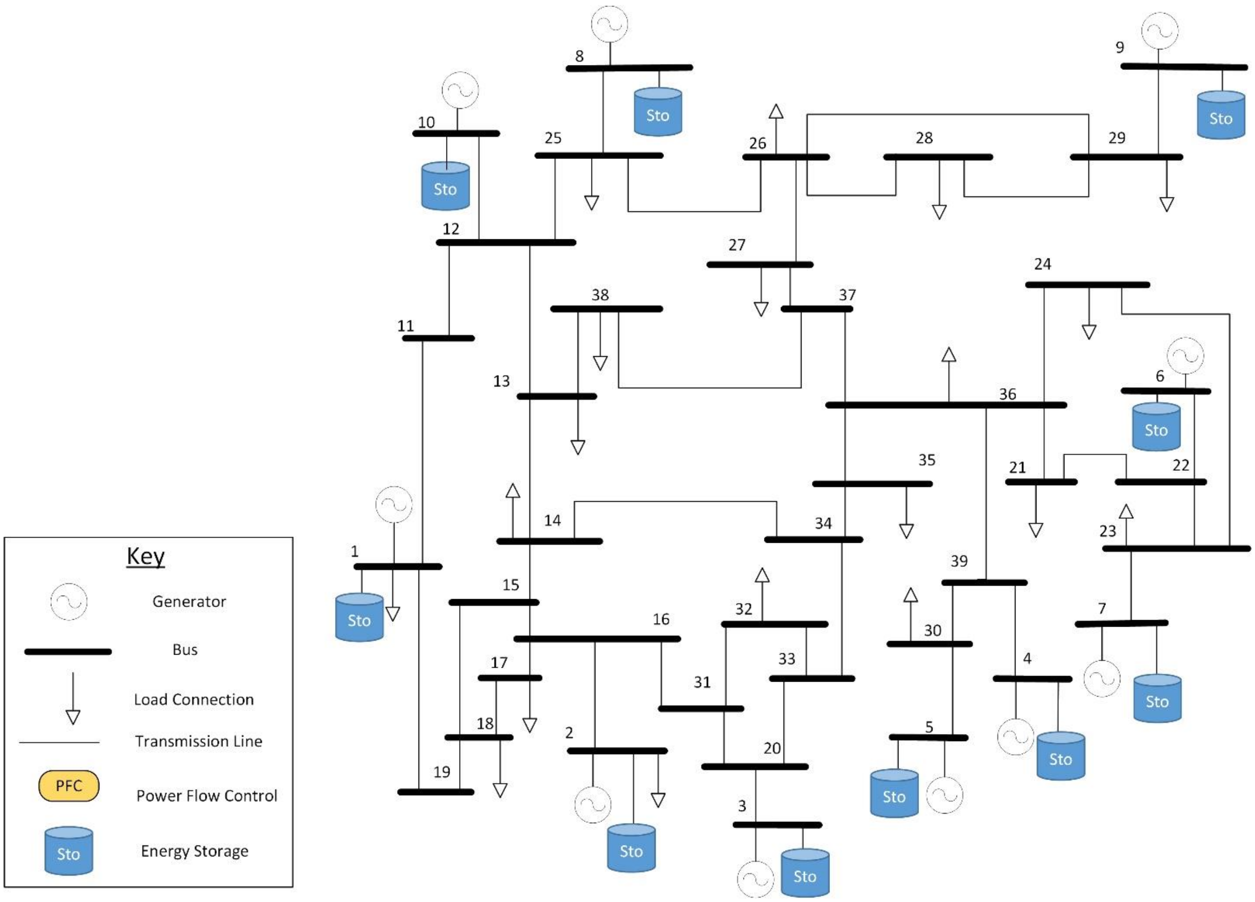

Figure 19 Storage on Generator-Only Buses

A primary difference in these strategies is the strcture for storage coordination and control. In strategy 1, ownership of the storage unit is likely to be in the hands of multiple distribution utilities, whereas in strategy 2 or 3 is it likely to be in the hands of transmission utilities or generator owners. This may have implications for storage operations, depending on the coordination strategy used.

Strategy 3 has two drawbacks: it places storage close in to generators and so can suffer from problematic interaction of power electronics with close in faults (if the storage device uses a power electroncis interface); storage located at generator buses is nto as effective as the other approiaches whern it comes to stabilizing transmission systems against distribution-edge based volatility.

Where storage allocation does not have coordination or ownership implications is the case of each storage unit operating autonomously. In this case, the storage is decentralized but not distributed.[29] Figure 20 shows such an arrangement.

[29] A decentralized system becomes distributed when the elements cooperate to solve a common problem. The cooperation mechanism is called coordination.

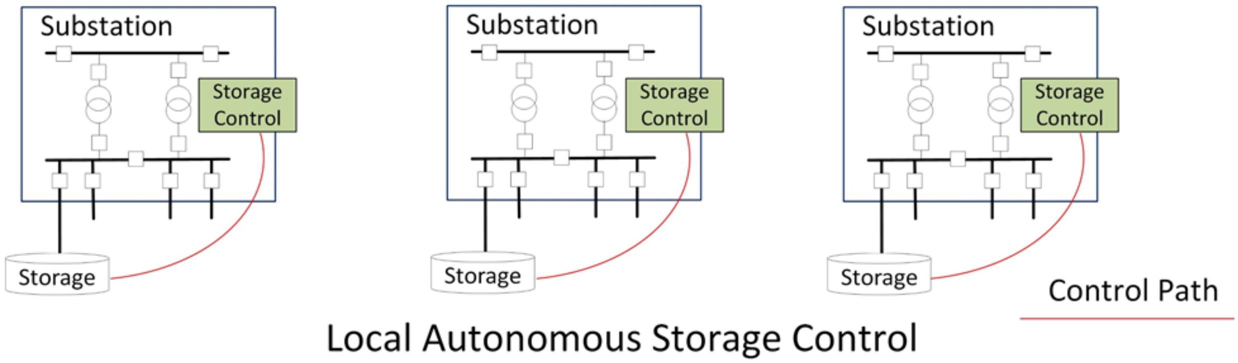

Figure 20 Autonomous (Decentralized) Storage Operation

Since the storage unit controls do not coordinate, ownership of the units does not impact storage control. However, the storage units are electrically connected through the grid and there is the potential for hidden coupling effects, leading to problematic grid behavior. By converting decentralized storage into distributed storage, the hidden coupling problems can be avoided and new system capabilities may be realized. This conversion is accomplished by coordinating the entire set of storage units.

<u>Coordinated Storage Networks (Transmission Level)</u>

By treating the set of storage units as an interconnected network, and by providing mechanisms for coordination of this network, the set of storage units may be managed to support system objectives related to resilience, operational flexibility, and reliability. Conceptually, such an arrangement would look like Figure 21.

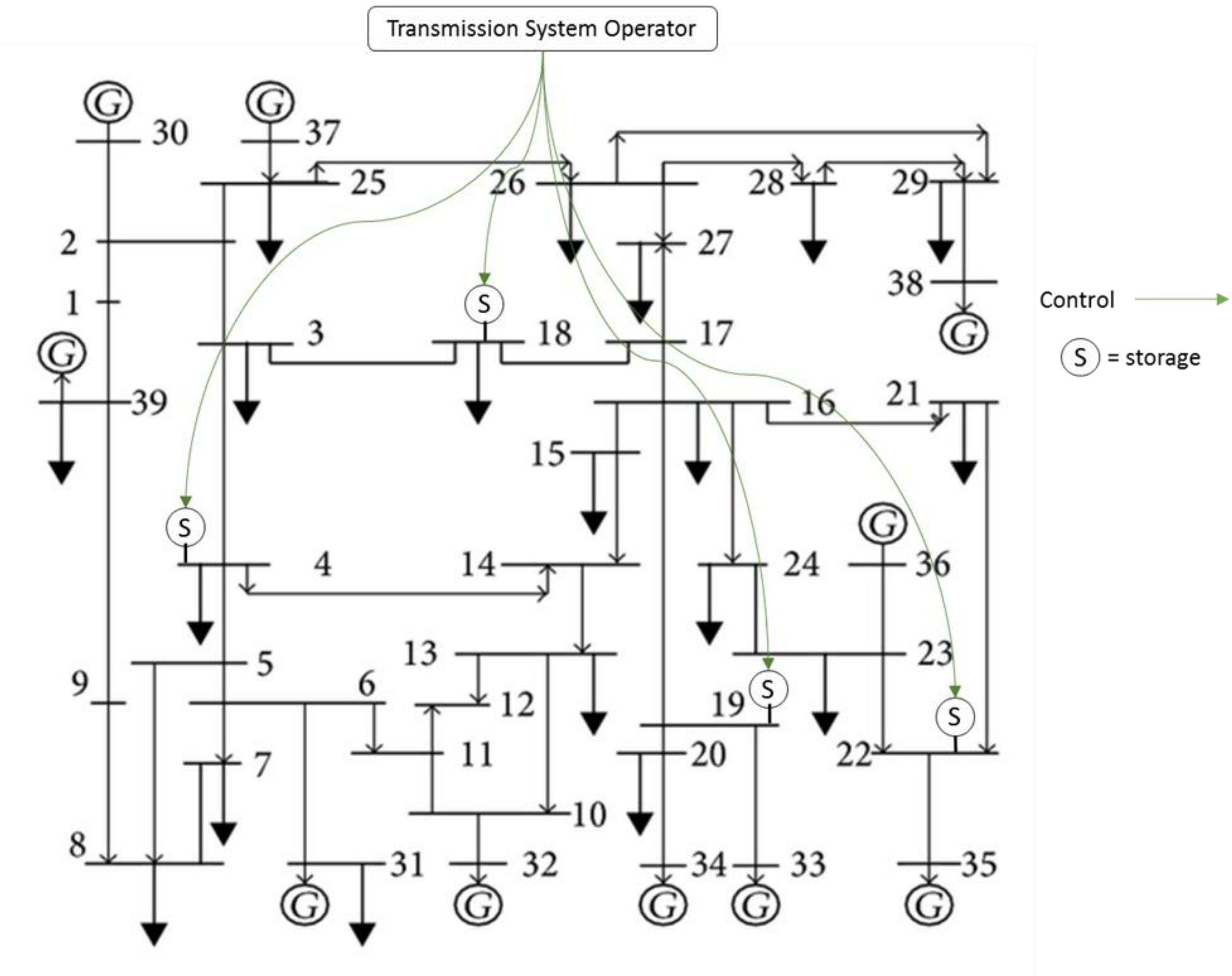

Figure 21 Conceptual Model of Storage Coordination Structure

Here the coupling of storage units is at the transmission level, but is it also feasible to interconnect at the distribution level, and thereby share storage across multiple distribution substation service areas.[30]

Actually, there are three storage network coordination structures to consider. The first is the most obvious and easiest to understand in terms of control operation: the centralized form shown in Figure 22.

[30] J Taft and R Huang, Distribution Storage Networks, PNNL-26598, June 2017, available online: https://gridarchitecture.pnnl.gov/media/advanced/Distribution_Storage_Networks_v0.3_PNNL.pdf

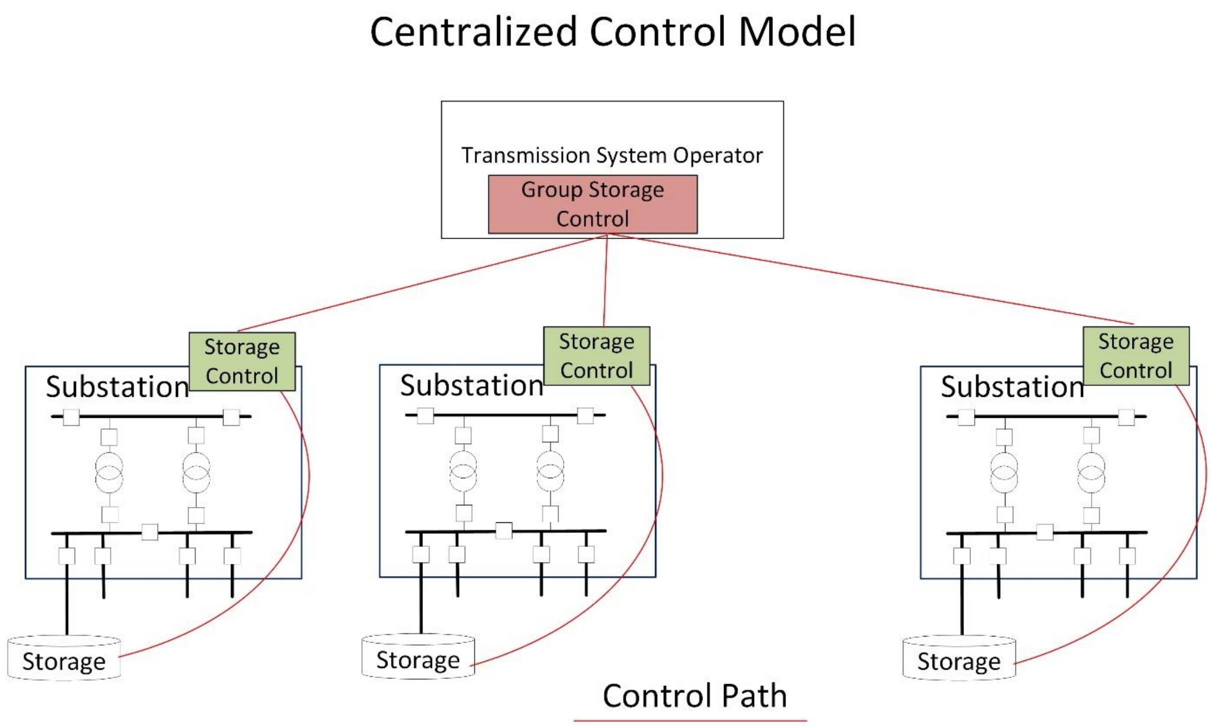

Figure 22 Centralized Storage Coordination

State of charge management is the responsibiity of the TSO in this model.

The second distributes the intelligence of the coordination mechanism and requires means to share information appropriately (as in any distributed control) since the information is not centralized. It offers considerable resilence against various forms of system and component failure but is harder to implement. State of charge mangement is a distributed function, something that is not well established in storage control theory. Figure 23 illustrates this structure.

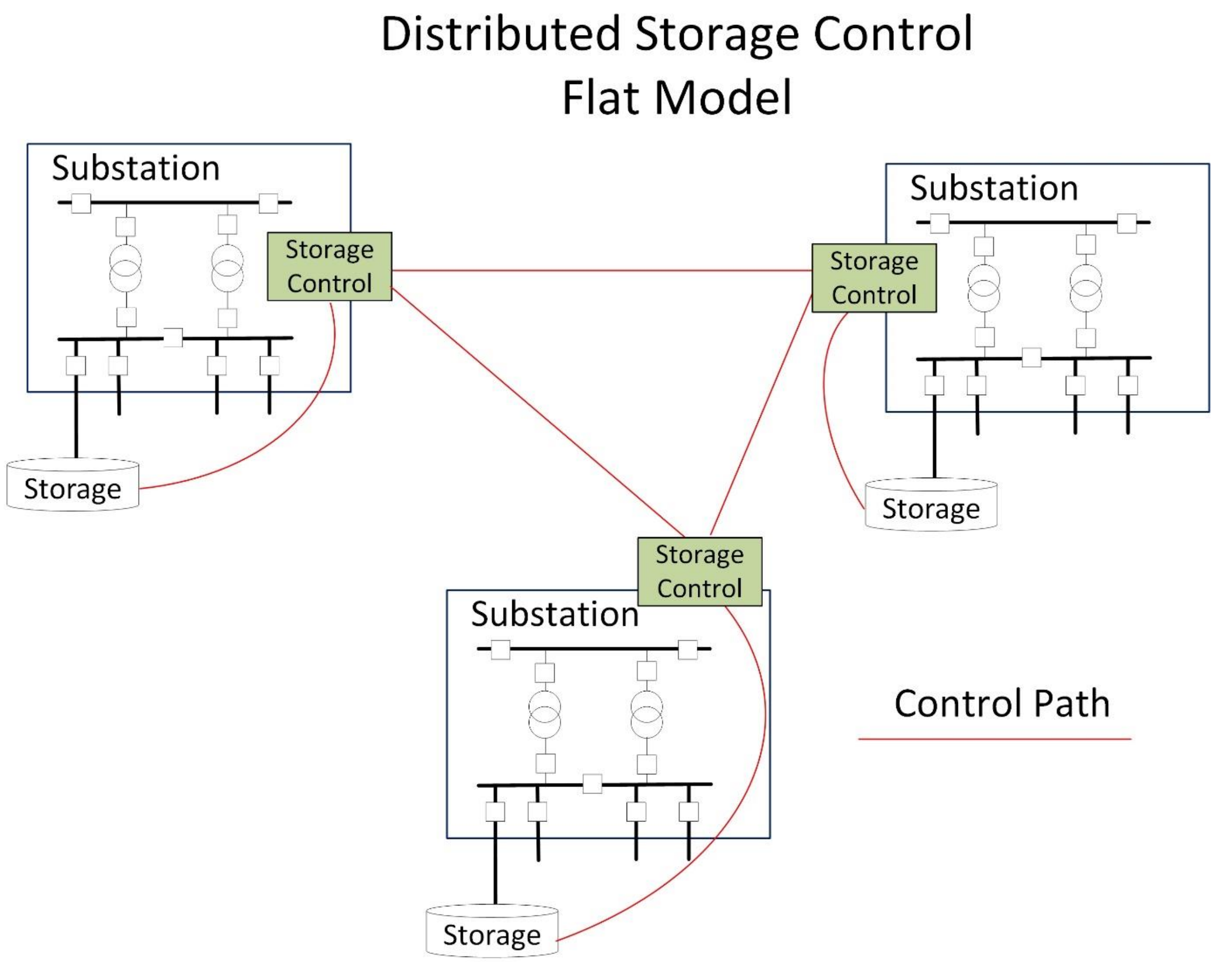

Figure 23 Distributed Storage Coordination Flat Structure

The third form is relevant when the storage units are owned by the distribution utilities but are to be operated (at least at times) for the benefit of the bulk power system. Presuming the TSO/DSO model poreviously discussed, this model is represented in Figure 24. In this mode, the TSO calls upon the DSO to provide grid operational support and the DSOs operate their storage (and any other resouces neeeded and available) to meet the system requirements, and also use the storage for distribution operational purposes. State of charge management for each storage unit is the responsibility of the distribution operator that owns it.

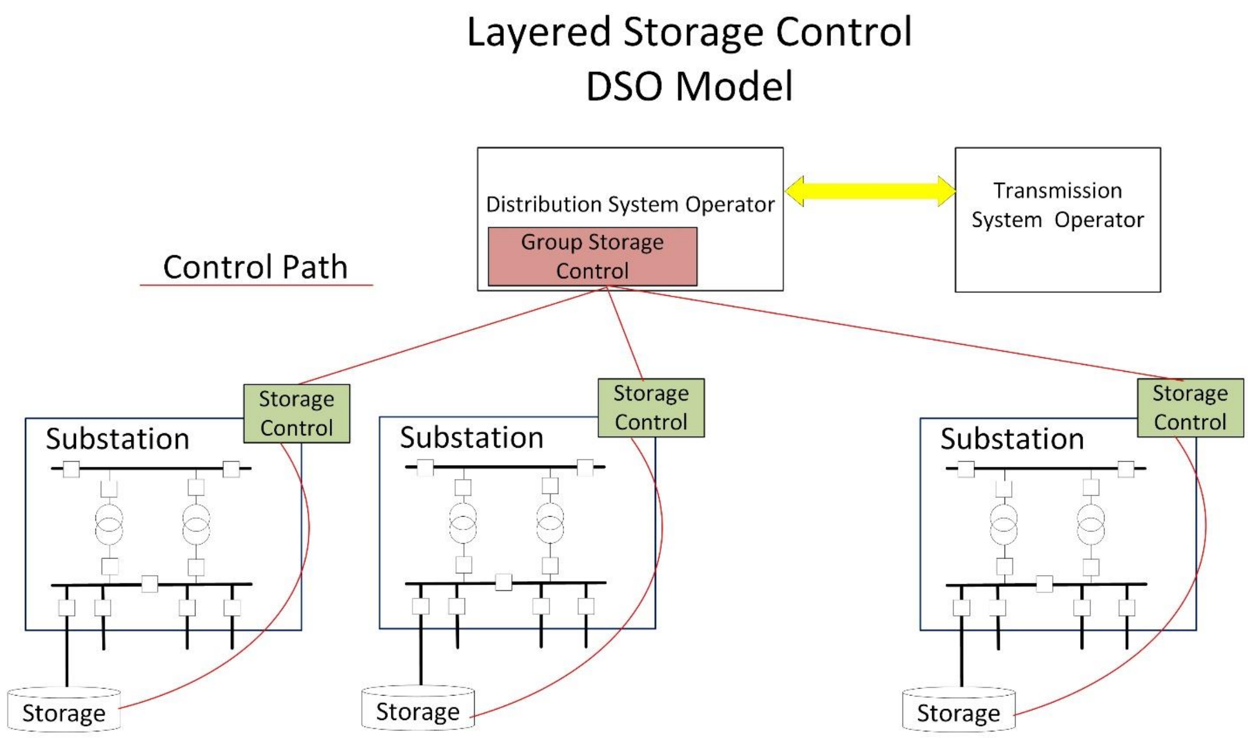

Figure 24 Layered Storage Coordination

In practice, a storage network architecture can use of several of these in a prioritized manner to handle various operating modes as follows:

- Primary Mode – use either the Centralized or Layered Model, depending on storage allocation
- Secondary Mode – in the case of a failure of the upper levels of control, fall back to the Distributed Flat model to provide the best operation given the semi-localized information constraints
- Tertiary Mode – in the case of widespread communication failure, each storage unit should default to a local operating mode designed for safe operation in the face of limited grid state information

Note that these three modes of coordination are characterized by progressively smaller zones of observability (system range over which state information is available to the device controller).

Specification 5 Details

5.1 Treat the combination of fast bilateral storage, power electronics interface, and advanced control as a core grid infrastructure element or building block.

5.2 Embed storage devices inside the Bulk Power System. This is separate from any units that are attached as ancillary servces devices.

5.3 Allocation of storage devices across a Bulk power System must take into account device ownership so as to resolve issues of communications, coordination, and control.

5.4 Treat the entire collection of storage units as a core infrastructure network, and provide a coordination mechanism that enables operation as an operational system, as opposed to individual attached services devices.

5.5 Provide a three –tier coordination mechanism, with progressive fallback based on reduction of observability zones (due to faults, failures, attacks, etc.), with built-in safe operating measures to deal with close-in faults, crew and public safety, etc.

Specification 6: Combined Gas/Electric Structure

6.1 Gas/Electric Resilience Loops

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 25 for an illustration of interconnected gas and electricity delivery systems. The interconnection is generally regarded as a dependency of electricity on gas and therefore represents a resilience vulnerability. However, the presence of gas fracking as it is practices in parts of the United States presents an opportunity to structure regional resilience into the combined system.

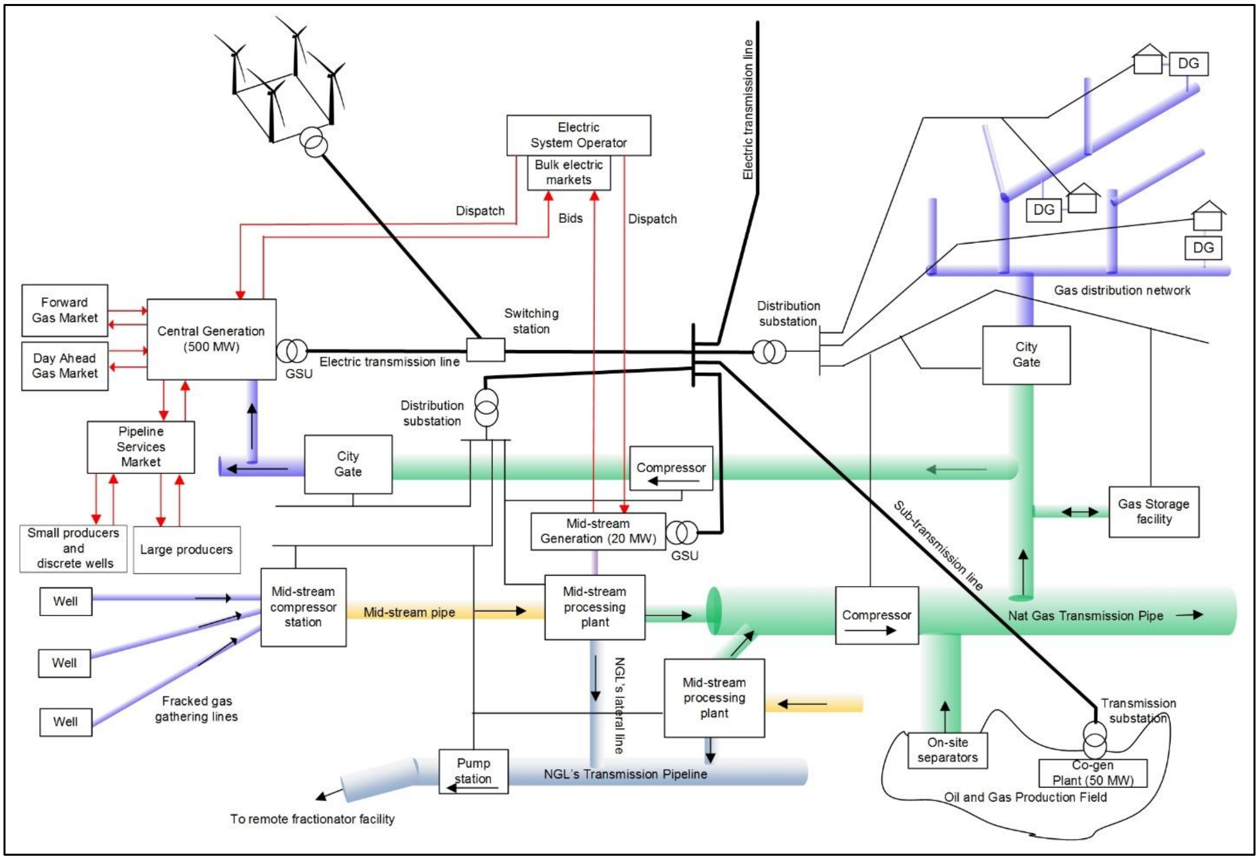

Figure 25 Combined Electric-Gas System Structure Illustration

Figure 26 illustrates the structural nature of this interdependence: a failure in the bulk electric system will hinder the delivery of gas and a failure in the bulk gas system will hinder electricity generation. Such a failure can even affect private standby or backup generators that would be expected to provide outage ride through if those generators are gas powered. This can be mitigated to some extent by gas line packing, but only as a very short term measure.

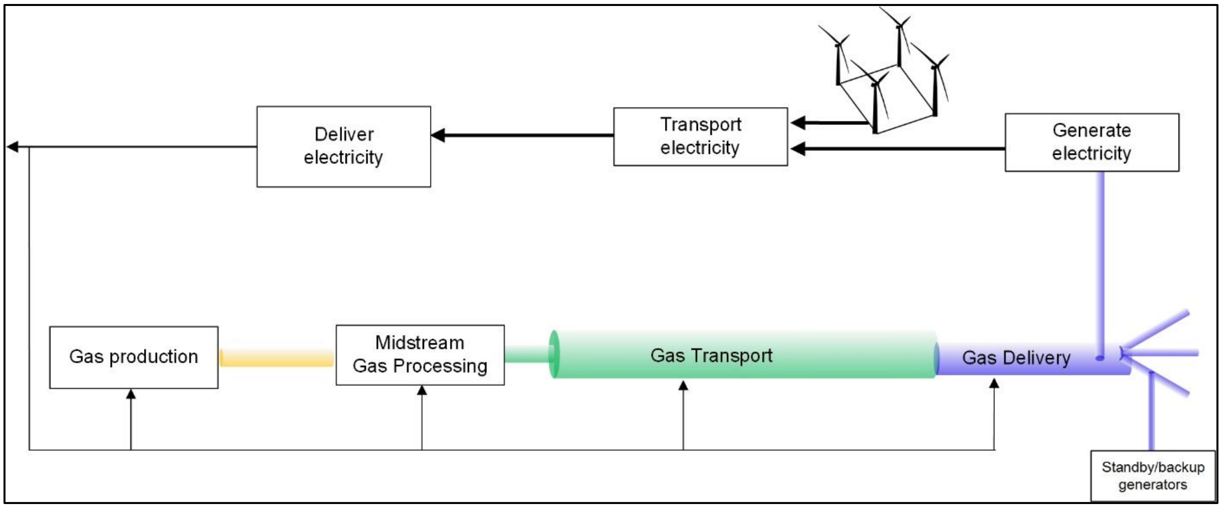

Figure 26 Essential Gas-Electric Interdependency Loop

Now consider the situation with fracked gas in Figure 27. Here midstream electric generation has been added adjacent to the cryogenic processing facility. This was originally developed because small gas producers had difficulty getting their gas to markets due to lack of availability of transmission pipeline capacity (capacity was bought up by the large producers). Generators of under 20 MW capacity placed at midstream processing plants take gas before it enters the transmission pipeline and use it to generate electricity that is injected into the local transmission system. The result is the creation of an inner resilience loop such that a failure in the bulk gas transmission system or the remote bulk electric generation/transmission system is mitigated locally by the gas-midstream generation-electric delivery loop for the region served by it. This keeps the gas flowing and electricity generation in operation, thus providing electric service for the local area despite a wide area blackout or bulk gas system failure.

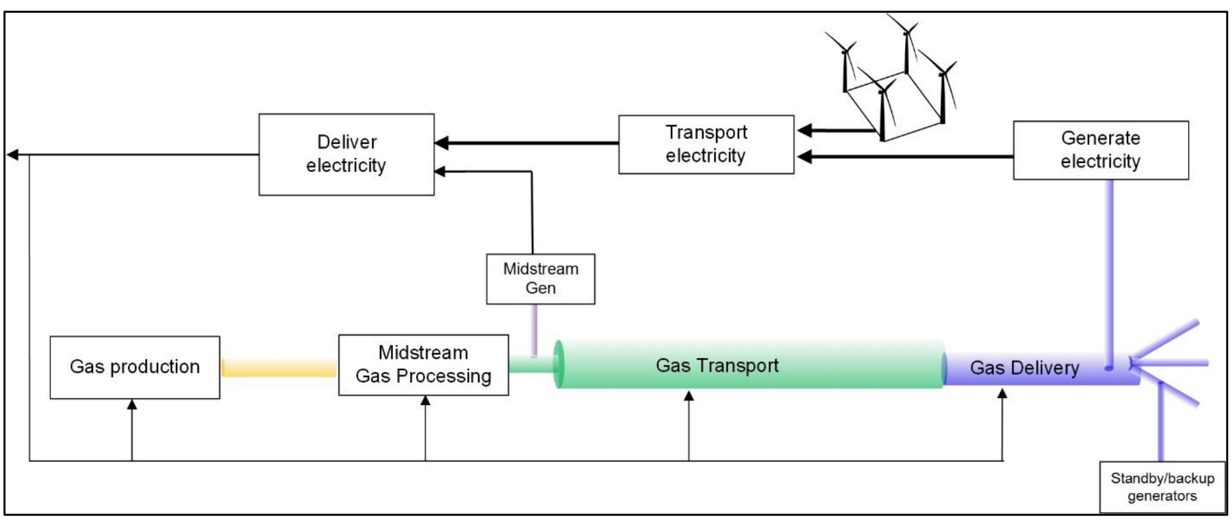

Figure 27 Gas-Electric Inner Resilience Loop

The inner resilience loop is a means of applying redundancy and distributed structure to address a systemic resilience vulnerability.

Specification 6.1 details:

6.1.1 Use small scale mid-stream generation to create resilience loops in electric systems powered by fracked natural gas.

6.2 Gas Electric Convergence

The widespread use of natural gas to fuel electronic generators has introduced new coordination and control problems. Experience with the polar vortex event in 2013-2014 highlighted some of these.

One problem was lack of natural gas and electric market synchronization. Figure 28[31] shows how the two markets had been operating in terms of timing. With gas markets closing after electricity markets, generators were forced to bid without assurance of fuel supply, which because an issue during spells of extreme cold, since natural gas is also used for space heating.

[31] Source for Figures 28 and 30: A. Zlotnick, et al., Grid Architecture at the Gas-Electric Interface, Los Alamos National Laboratory, LA-UR-17-23662, May 2017, available online: https://gridarchitecture.pnnl.gov/media/advanced/Gas_grid_architecture.pdf

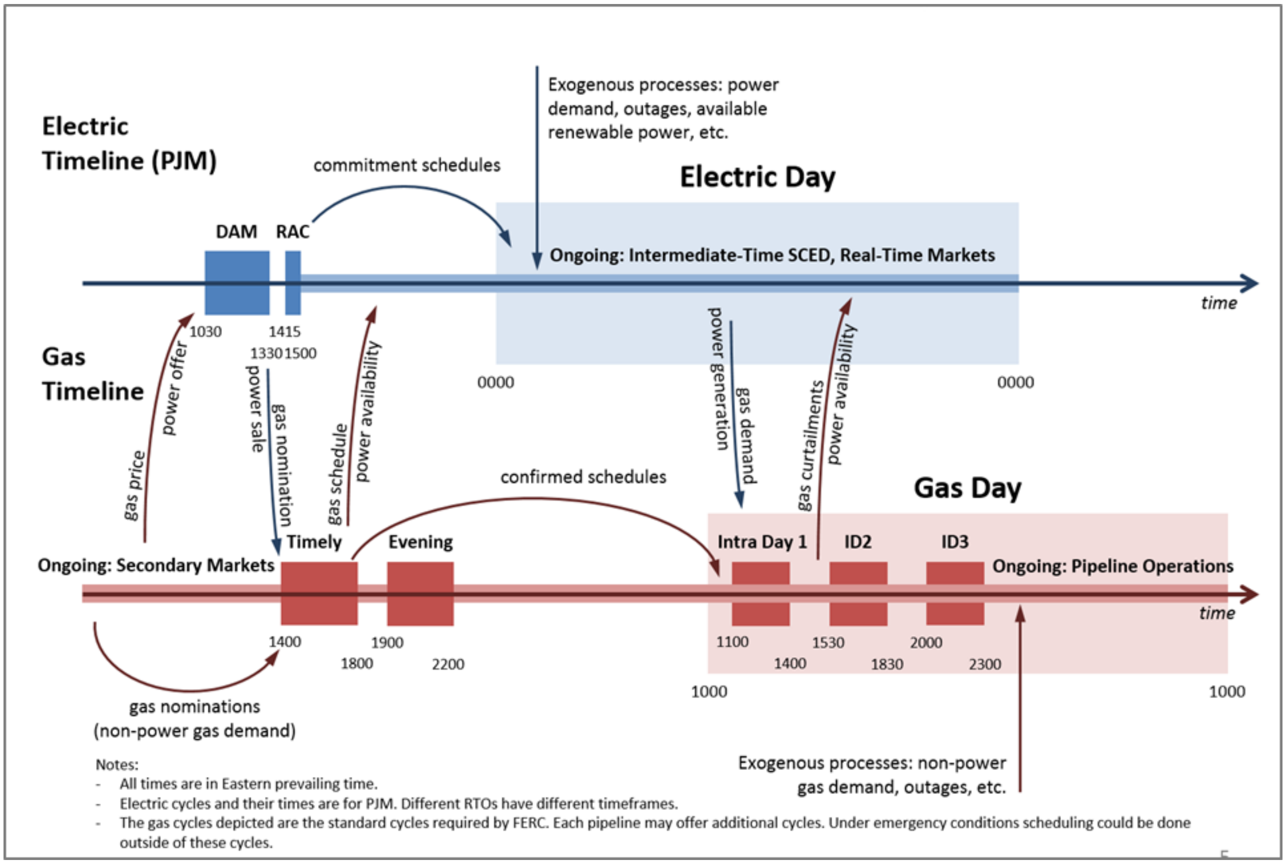

Figure 28 Existing Gas and Electricity Market Cycle Timing

A second issue was lack of ability of each system operator (gas and electric) to understand operating conditions of the other so as to be able to make real time adjustments to operating parameters. Finally, the gas transport systems operate better with constant flow rates, whereas the gas turbine generators have dynamic and peaking behavior that can change on short notice. The gas systems can provide a degree of buffering by using line packing given sufficient advance notice, but without visibility into electric system forecasts and planned dispatch, as well as real time behavior, not much can be done.

These issues can be addressed by using a stack of coordination elements, as shown in Figure 29.

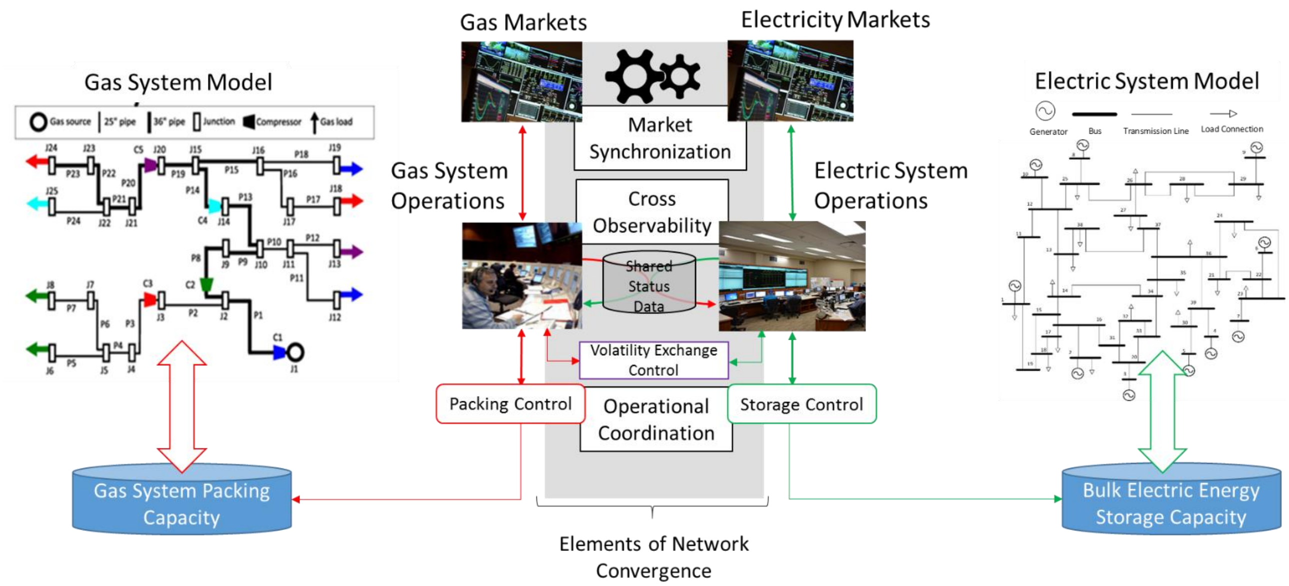

Figure 29 Gas-Electric System Convergence Structure

The structure for convergence of these two infrastructures has three tiers:

1. Market synchronization
2. Cross observability
3. Operational coordination

Market Synchronization

FERC has created an order that increases the electric industry's scheduling flexibility by increasing the number of the intraday gas nomination cycles (from 2 to 3) and introducing multi-party gas transportation contracts.[32] Timing of the gas nominations cycles has been better harmonized with the needs of the electric industry and their volatile loads. Figure 30 shows a modified market schedule developed by Los Alamos National Laboratory to synchronize the markets.

[32] Docket No. RM14-2-000; Order No. 809, Coordination of the Scheduling Processes of Interstate Natural Gas Pipelines and Public Utilities, April 2015, available online: https://www.ferc.gov/whats-new/comm-meet/2015/041615/M-1.pdf .

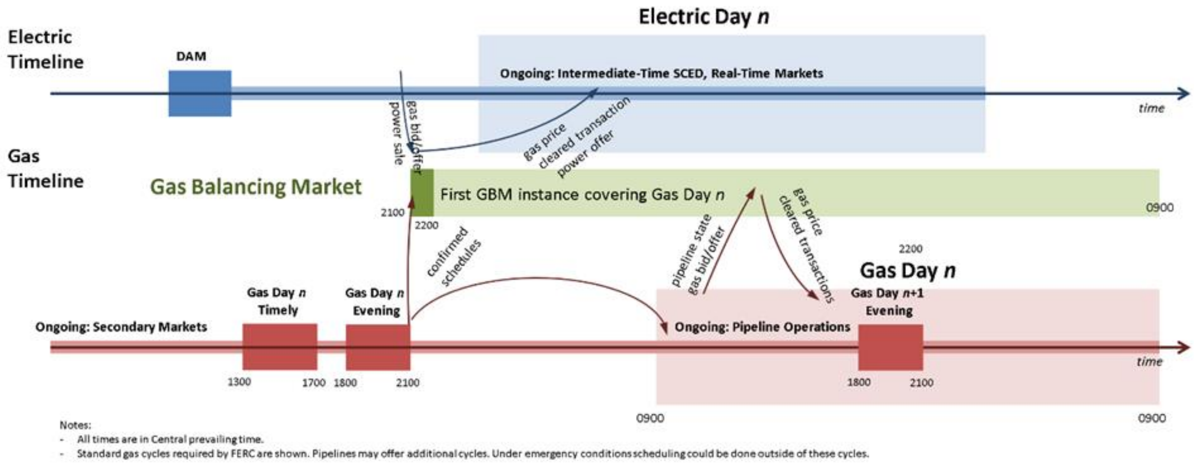

Figure 30 Gas Electric Market Cycle Synchronization

Cross Observability

Each infrastructure has its own operations centers, instrumentation and telemetry, and roughly corresponding state variables. Similar problems exist in terms of capacity constraints, scheduling, and congestion management. Pipeline operators do not have good methods to optimize compressor and regulator operation to maximize system throughput under transient conditions. Proposals have been made to create Locational Trade Values (LTVs) of natural gas at all nodes of the gas pipeline network, similar to electric system Locational Marginal Prices (LMPs)[33] and for similar purposes.

Coordination of the two infrastructures requires some amount of state information sharing between system operators, a fact recognized by FERC.[34] A structure for enabling such cross-observability can be modeled on the distributed data management platforms for PMU networks in bulk power systems (see Specification 3). Each system operator must have control over the information it shares and sharing must be done in a manner consistent with information access rules for the markets involved.

Operational Coordination

First order operational coordination already exists in the form of the controls and processes needed to deliver natural gas to the generators. What does not exist is a means to take advantage of both gas system packing capacity and (future) electric system energy storage capacity (see Specification 5). The new coordination and control problem is to jointly manage and optimize the use of the buffering capacity on both sides the gas-electric interface to match the volatility requirements of each side to the

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[33] A. M. Rudkevich and A. Zlotnik, Locational marginal pricing of natural gas subject to engineering constraints, 50th Hawaii International Conference on System Sciences (HICSS). IEEE, 2017, available online: https://pdfs.semanticscholar.org/23b0/81ddd03fbd1a5ec5a16b9ac3f5009911459d.pdf

[34] Docket No. RM13-17-000; Order No. 787, November 2013, Communication of Operational Information Between Natural Gas Pipelines and Electric Transmission Operators, available online: https://www.ferc.gov/CalendarFiles/20131115164637-RM13-17-000.pdf .

other, a process called Volatility Exchange Control (VExC). Gas system operators could optimize their line packing if they had a view into upcoming electric generation behavior. But they only have so much capacity. Given some, amount of bulk electric energy storage, electric system operators could perform some amount of generation dynamics leveling, but again the capacity to do so would likely be limited. The purpose of Volatility Exchange Control is for the two system operators to collaborate on the coordination of both sets of buffer capacity to manage or even optimize gas flow-to-generation use dynamics. The mechanism would involve the system operators reaching agreement at the gas-electric interface on flow dynamics, and then each managing its buffer capacity accordingly. For the electric system operator, this is essentially the same approach as dealing with DSOs (See Specification 1) at the T/D interface.

The general problem of defining the nature and functions of the Gas/Electric interface could benefit from both Grid Code[35] and GWAC Stack[36] concepts.

Specification 6.2 details:

6.2.1 Use three tier coordination between Electric System Operators and Gas System Operators.

6.2.2 Synchronize market cycle timing of respective infrastructure markets.

6.2.3 Use a distributed data management platform for sharing selected information for cross observability.

6.2.4 Implement Volatility Exchange Control to jointly manage buffer capacities in the gas and electric systems to match flow dynamics.

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[35] JD Taft, Architectural Basis for Highly Distributed Transactive Power Grids: Frameworks, Networks, and Grid Codes, PNNL-25480, June 2016, available online: https://gridarchitecture.pnnl.gov/media/advanced/Architectural%20Basis%20for%20Highly%20Distributed%20Transactive%20Power%20Grids_final.pdf

[36] SE Widergren, et al., Interoperability Strategic Vision: Enabling an Interactive Grid, PNNL-26338DRAFT, April 2017, available online: https://gmlc.doe.gov/sites/default/files/resources/InteropStrategicVision2017-04-11.pdf

Specification 7: Grid Control and Market-Control Structure

Many methods exist for making parametric changes to transmission grid operation, including generator and ancillary services dispatch, Volt/VAR regulation, frequency regulation, and use of flow control technologies.[37] In the traditional grid control stack, it is common practice to set values for real and reactive power generation, phase shifter angles, net interchange, load shedding, DC transmission flows, control voltage settings and LTC transformer tap settings regardless of whether the system operator uses merit-order/security-constrained economic dispatch or wholesale organized market mechanisms as part of the grid management scheme, simultaneous solutions are determined for a large number of control elements on day-ahead, intra-day hourly, 15 minute, 5 minute, and 4-6 second cycles (depending on the level of control being referenced). Figures 31, 32, and 33 illustrate three existing approaches to the primary process flow for BPS system operations where organized wholesale electricity markets exist.

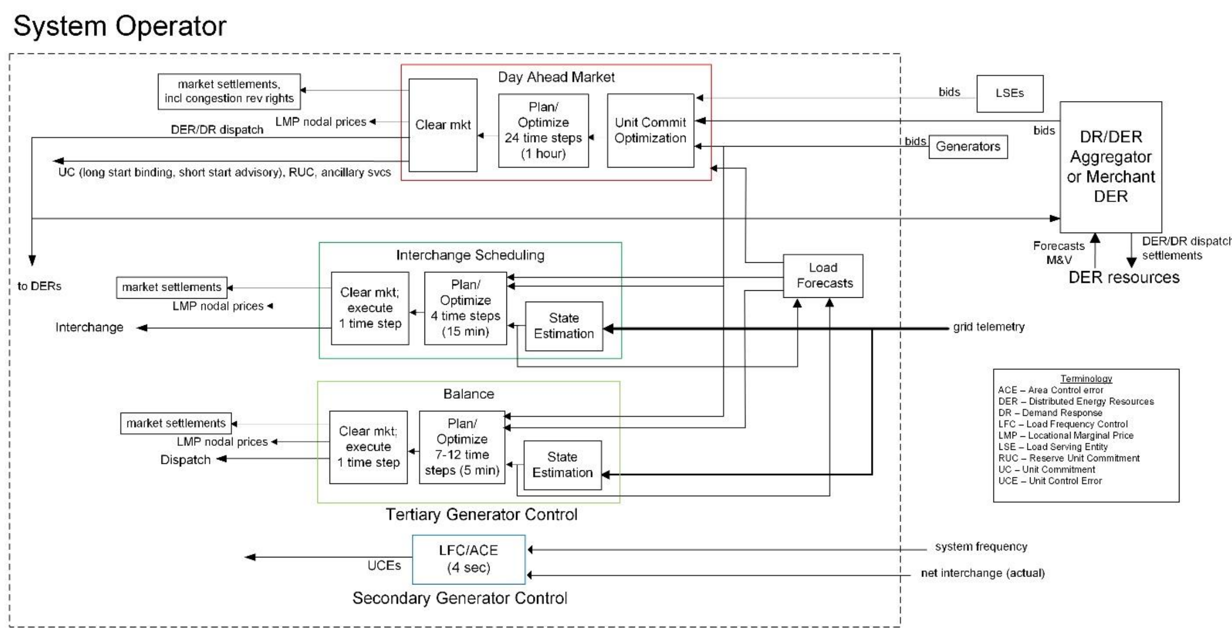

Figure 31 Market-Control Interchange/Balance Model

[37] Two standard flow control technologies in particular are phase shifting transformers and variable frequency transformers. Note that these are used primarily at the edge of the transmission system (e.g. for interchange), not internally in the transmission system.

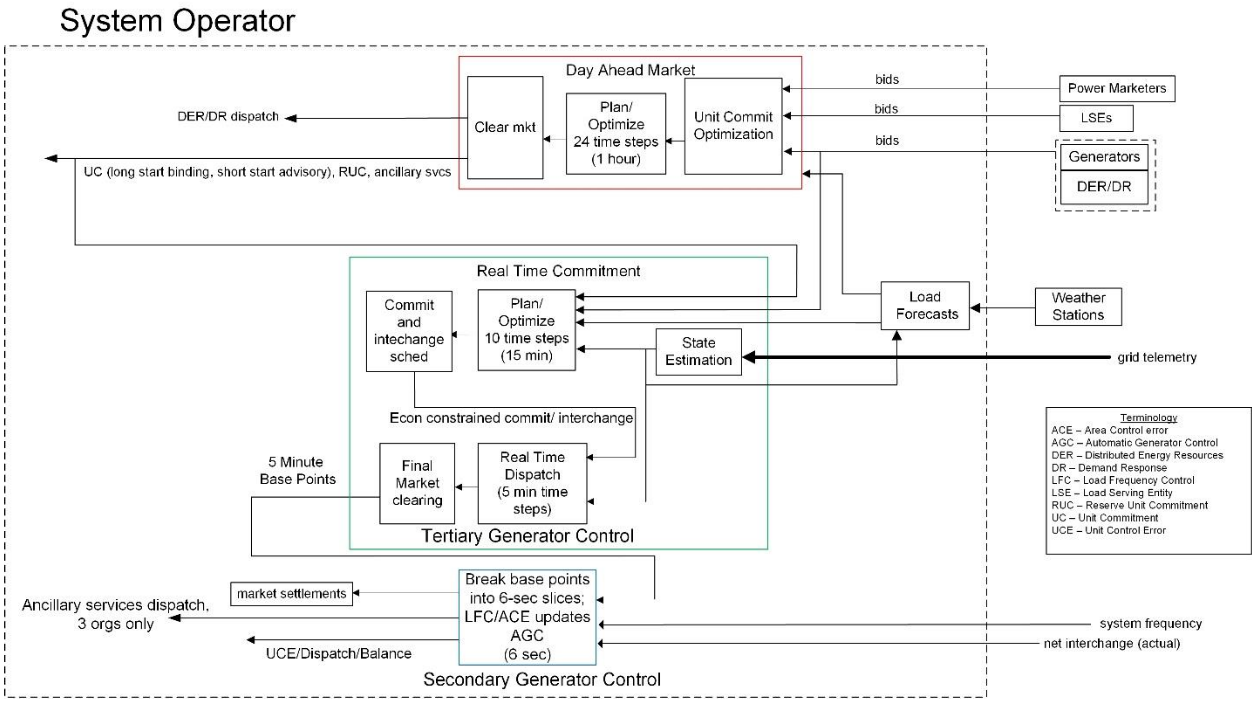

Figure 32 Market-Control: Real Time Commitment Model

In those regions where no such electricity markets exist, TSOs use top level methods based on merit order and security constrained economic dispatch, which work in a similar fashion but without the market clearing component. Pure market approaches and pure control approaches are debated in the industry, but in fact the two methodologies are complementary.[38]

[38] JD Taft, Electric Grid Market-Control Structure, PNNL-26753, June 2017, available online: https://gridarchitecture.pnnl.gov/media/advanced/Market_Control_Structure_v0.2.pdf

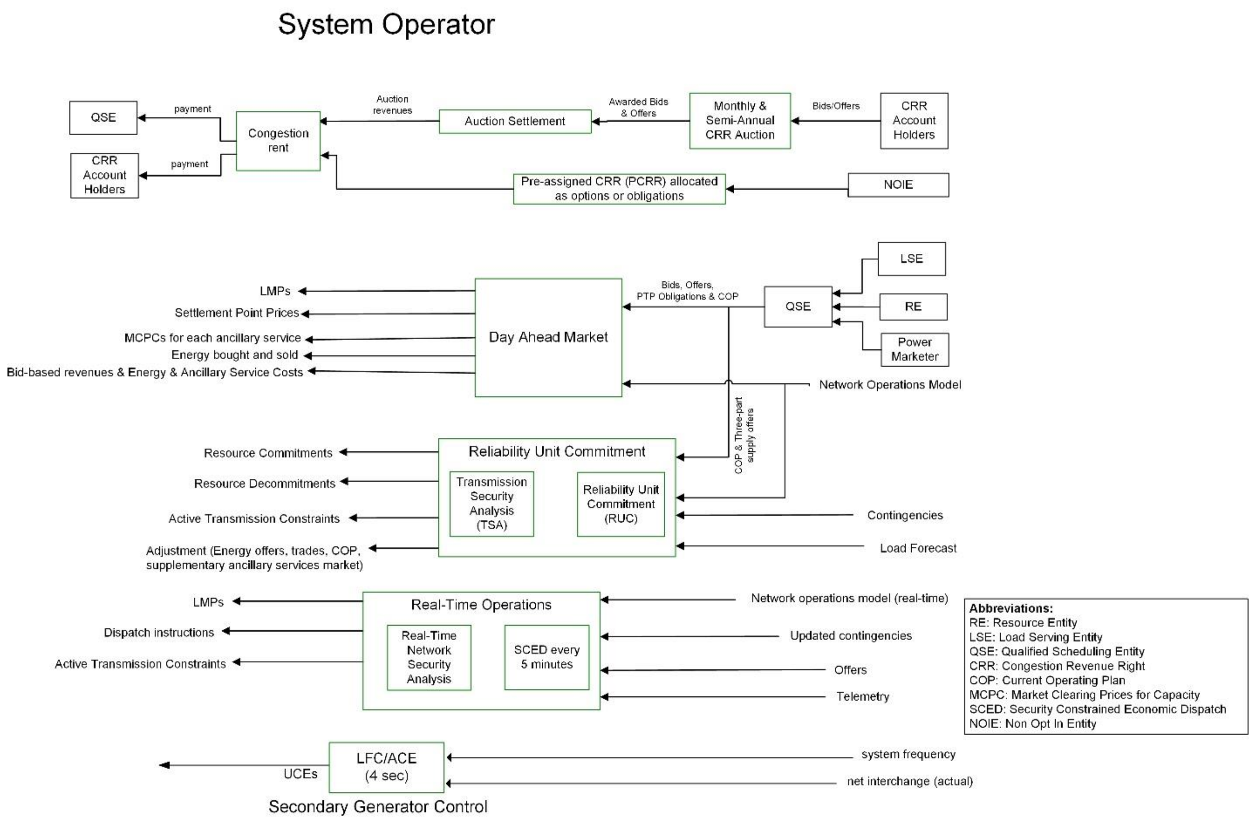

Figure 33 Market-Control: Reliability Unit Commitment/Real Time Operations Model

<u>Grid Control</u>

The traditional grid control problem has included multiple elements as shown in Figure 34:

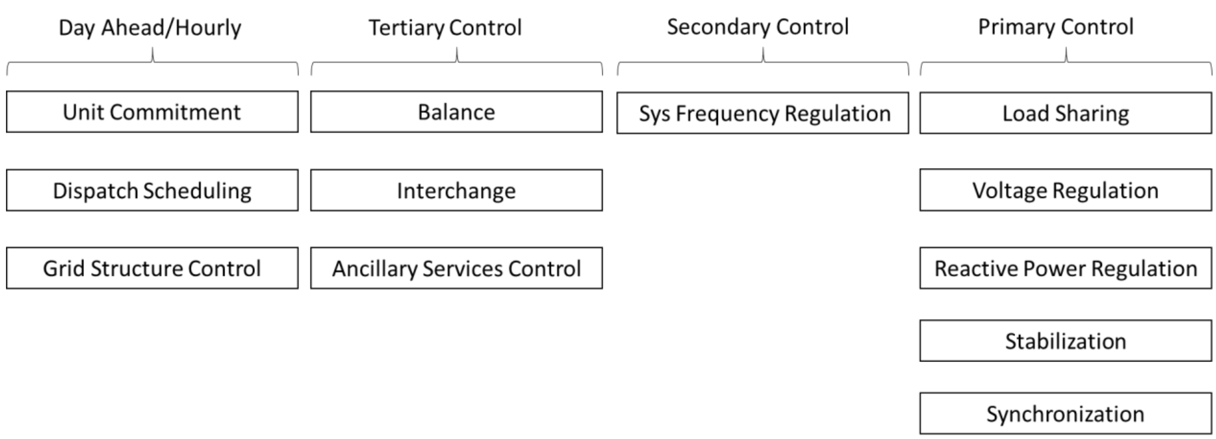

Figure 34 Traditional Grid Control Stacks

This set of stacks (separated by time scales) represents a BPS view, but has a strong homolog at the Distribution level. This homolog is growing stronger as Distribution systems gain edge-based generation and storage and as distribution systems adopt more autonomy via structures such as microgrids and community-based energy resources.

Emerging technologies and changing requirements have expanded the grid control problem in the significant ways:

1. Use and management of distribution level generation
2. Use and management of bulk energy storage
3. Availability of flexible flow control

The first of these is dealt with in another reference architecture; suffice to say here that the proliferation of distribution connected generation has already been noted to cause reverse power flows into the bulk system on systems with high solar PV penetration. The second has implications for both transmission and distribution and will be discussed here in the context of transmission. The third is an emerging transmission issue.

At the BPS level, structure control is integrated with other aspects of system control, such as dispatch and balance.

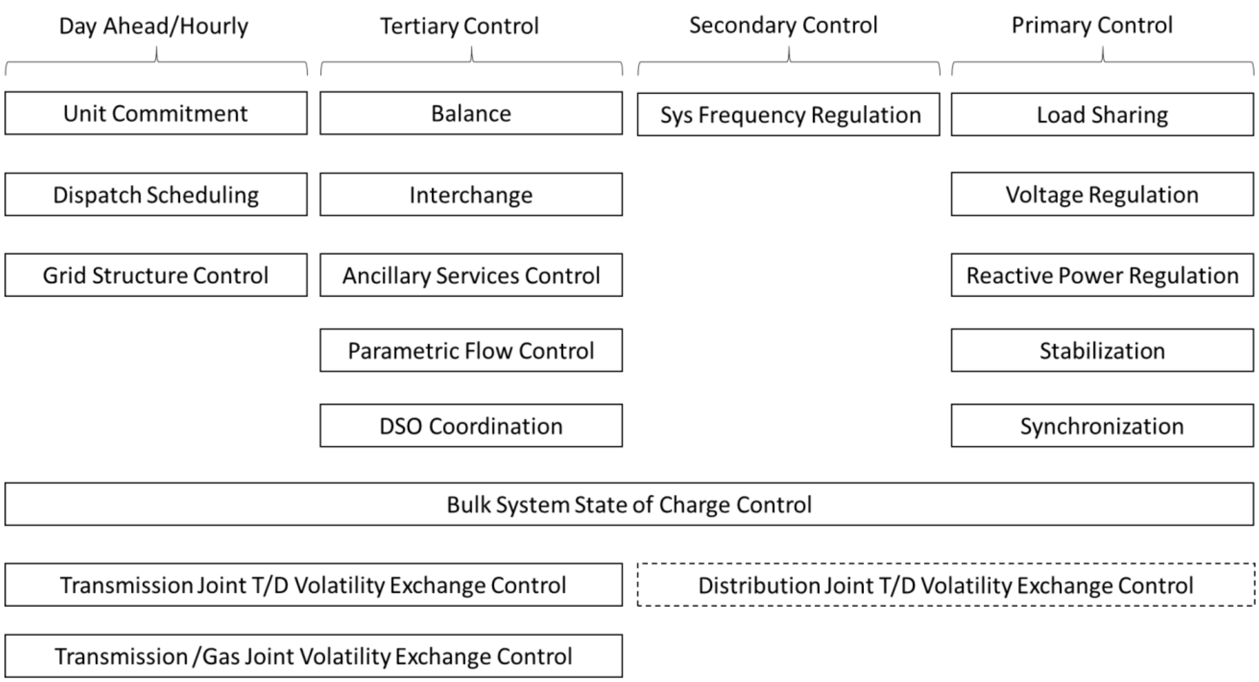

Figure 35 Emerging System Control Stack with Transmission-Only Bulk Storage

In Figure 35, bulk energy storage is presumed to be connected at the Transmission level only (see Figure 18) and therefore controlled by TSOs and TOs. Hence Bulk System State of Charge (SoC) control spans the entire time spectrum.

In Figure 36, bulk energy storage is presumed to be in the T/D substations (see Figure 17) and so the primary and secondary aspects of SOC control are the responsibilities of DSO and DOs. Use of such storage by the TSO (day-ahead and tertiary) is via the DSO interface (see Specification 1).

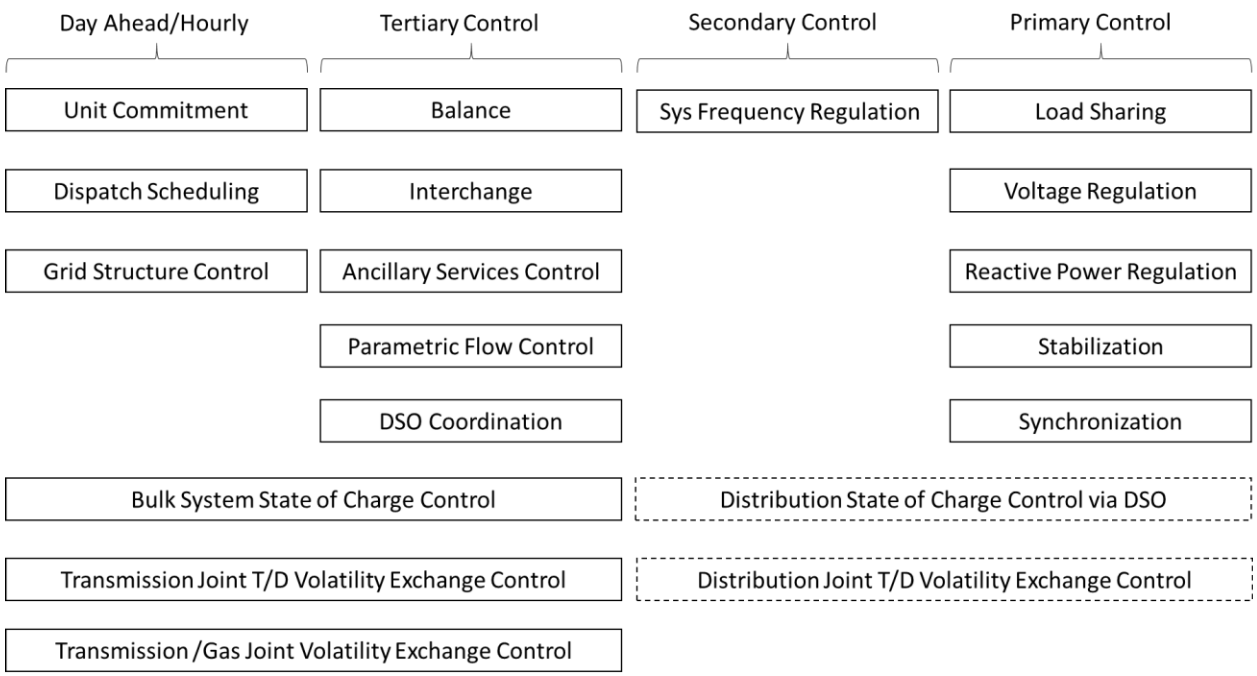

Figure 36 Emerging System Control Stack with Transmission/Distribution Substation Storage

<u>Implications for Market-Control Operations</u>

The foregoing discussions have several implications for market-control operations for electric power systems:

- The use of storage and parametric flow control inside transmission systems has the potential to reduce or eliminate the need for congestion revenue rights and LMPs.
- The introduction of SoC control and parametric flow control inside transmission systems causes the optimal power flow and dispatch problems to become increasingly computationally complex due to the assed degree of freedom. This increase the requirements on computational algorithms and resources to complete the calculations within the standard time cycles.
- Volatility Exchange Control (VExC) is a new control problem for the grid. The problem manifests itself in several ways, including duck curves, volatility export from distribution into BPS, and gas-electric “meshing friction.” VExC has two forms: intra-system (transmission-distribution coordination), and inter-system (gas-electric convergence).

The first and second bullets above suggests a potential significant shift in how real time electricity markets are designed and operated. Since the use of parametric flow and storage are emerging, it is not yet known if this combination can completely eliminate transmission congestion issues.

Specification 7 details:

7.1 Use layered coordination structure to unify coordination in electric power systems and to allow transmission systems to treat distribution systems as a combination of load and generation tie points, connected at the T/D interface and coordinated via DSOs.

7.2 Expand the standard optimal power flow, unit commitment, and dispatch control methods to include storage SoC control and internal parametric transmission flow control.

7.3 Provide a means for intra-infrastructure Volatility Exchange Control at the T/D interface via TSO/DSO coordination and the use of bulk energy storage.

7.4 Use extended Code stack models to define interfaces between electric systems and other infrastructure such as natural gas systems.

7.5 Provide the means for gas-electric Volatility Exchange Control via gas-electric operational coordination and the use of gas system packing and electric system bulk energy storage.

Specification 8: Wide Area Closed Loop Control

Stabilization is one of the class of real time grid control functions (see Figure 34). As such, timing is critical and when implemented in a wide area closed loop form, communication latency can become a critical factor.

An example is the use of transmission level power electronics in the form of a Unified Power Flow Controller (UPFC) device, combined with a phasor measurement unit, to automatically dampen inter-area oscillations.[39] Often in power systems control work, the communication network has been assumed to be more or less ideal but in practice actual network latency can be quite detrimental to closed loop control. Figure 37 shows a schematic version of such a control with a PMU providing the sensor feedback signal to the inter-area oscillation damping controller. The controller sends commands to the UPFC device, which is the final control element that dampens the oscillations and stabilizes the system.

In this example, a UPFC is connected between two system buses, and generator phase angle is monitored at Bus 6 via PMU. The PMU data stream goes to the UPFC controller and the controller commands stream to the UPFC itself. In the simulation developed for this case a fault is introduced at bus 21 and the behavior of the bus 6 generator angle is monitored during the time the UPFC is providing damping of inter-area oscillation, under three different communication latency scenarios.

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

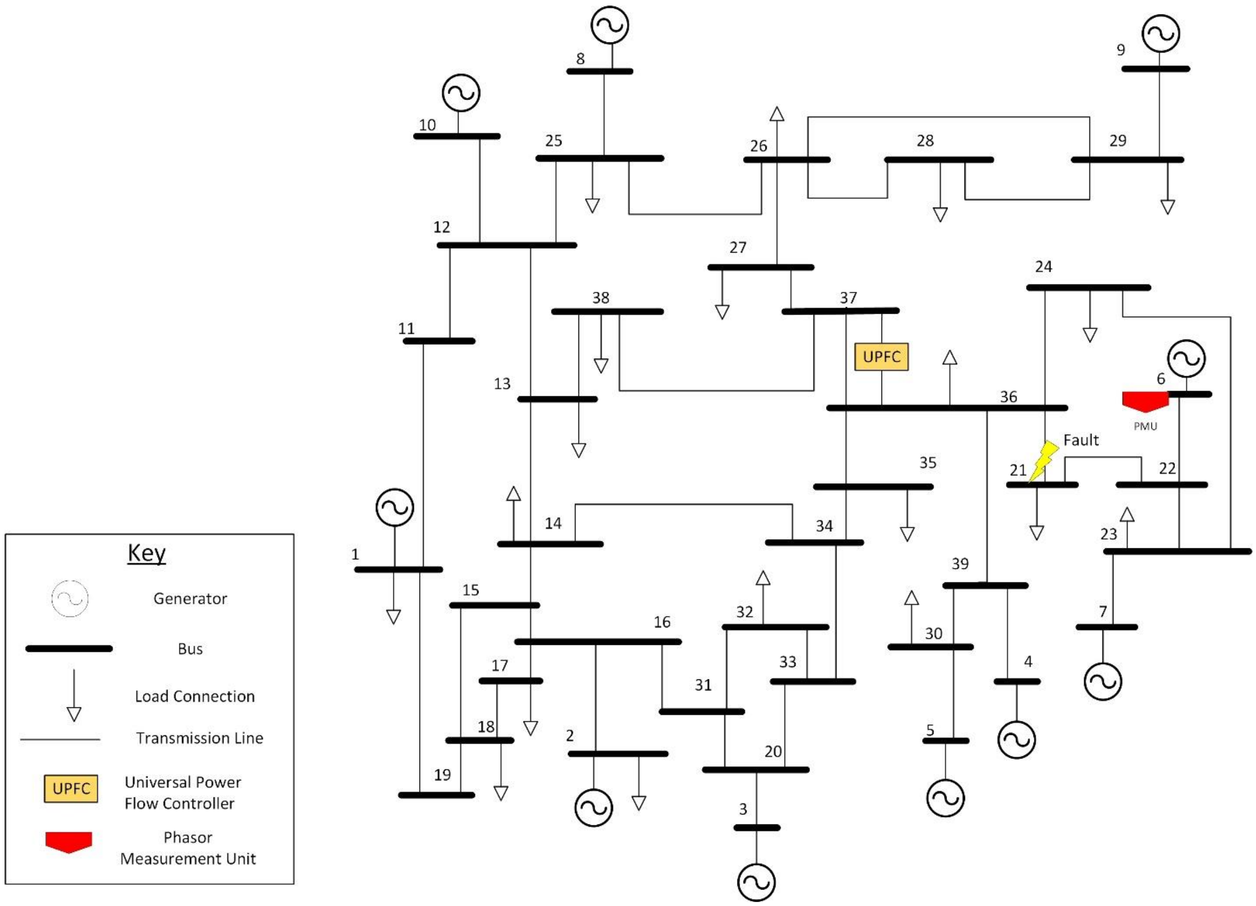

Figure 37 Wide Area Damping Physical Arrangement

Figure 38[40] shows a graph of the damping behavior of a UPFC system with differing amounts of latency in receiving the remote PMU signals. The graph depicts the generator angle at bus 6. As can be seen, latency can cause the damping control to destabilize so that the oscillation does not dampen out.

A simple closed loop damping control suffers from the problem that it does not have the ability to adapt to variations in communications latency, but these variations can occur without notice. A different structure that provides for *interaction between the damping controller and the communication network* (as opposed to treating the communications network as uncontrollable) employs an application interface into the communications network. Software Defined Networking (SDN) provides a mechanism for this.

SDN is defined by the Open Networking Foundation as “the separation of the communication network control and data plane that decouples the network control and forwarding functions enabling the

[40] From a simulation of the 10-Generator 39-Bus system with a UPFC connecting buses 36 and 37 for oscillation damping, with various measurement communication delays.

network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services."[41]

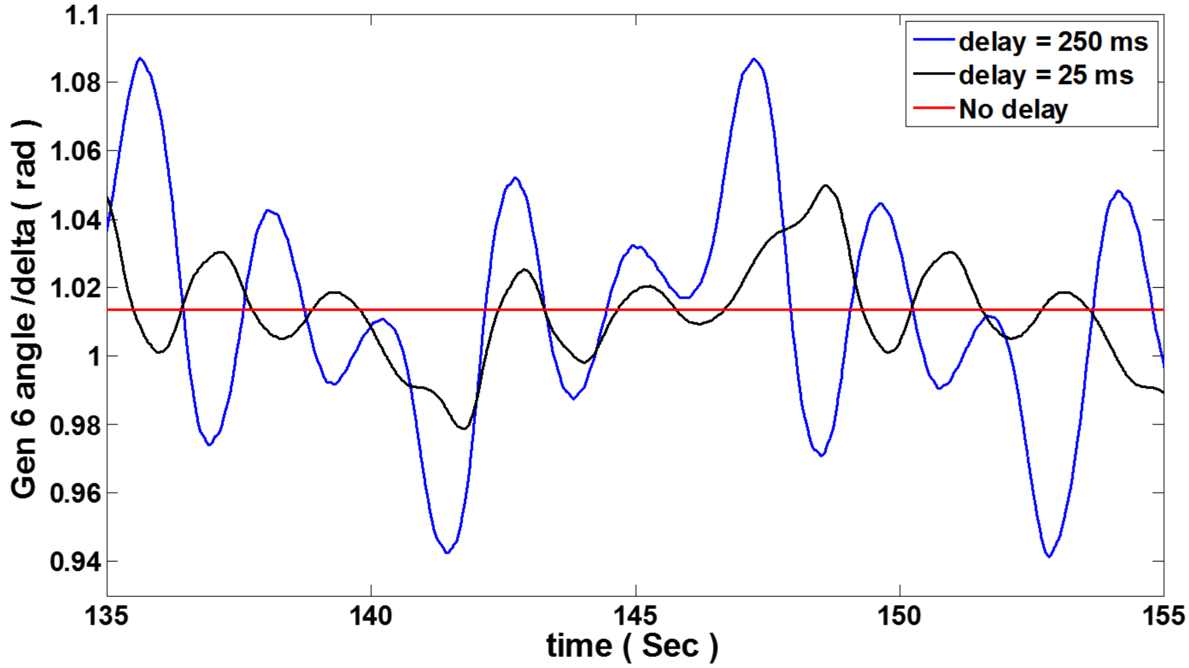

Figure 38 Closed Loop Damping Behavior under Differing Communication Latencies

In general, multiple sensor signals may be used as feedback inputs to the closed loop control. Figure 39 shows such a damping control approach in schematic form. From this representation it is easier to see the essential structure: a damping control feedback loop is closed around the system for stabilization, and a second loop provides interaction between the damping controller and the network by way of the Software Defined Networking (SDN) interface.

Both measurement and control signals may pass through the communication network (depicted here as a cloud) although in some arrangements the controller is co-located with the final control element so no wide area networking is needed for the control signal.

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

- The controller uses data on network conditions and performance to adjust its own compensator parameters and sample rates to be stable under existing network conditions such as path latencies, thus adapting to overall system dynamics

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

- The controller adjusts network paths and other parameters to fit the requirements of the control algorithm, this tuning the network to controller specifications

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

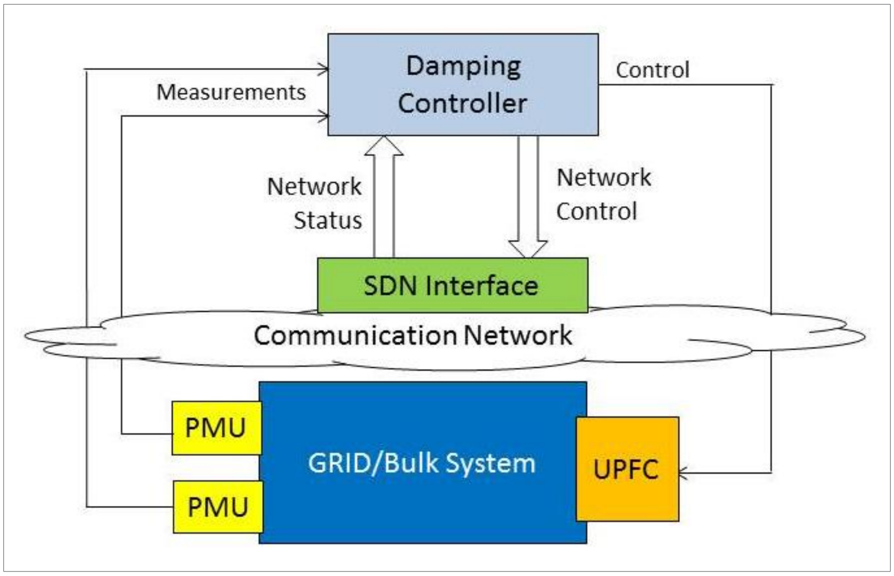

Figure 39 Combined UPCF/SDN Control Structure

Communication network performance is not fixed and the network elements can and do introduce latencies, jitter, and skew that can affect loop stability and Protection and Control (PAC) performance. Large networks can introduce variable delays (which are time-varying as the network changes routing), and skew when different paths exist for multiple sensors sending data to the same controller or when the controller is sending commands to multiple final control elements. Simply specifying that the network be deterministic is unrealistic for wide area control; while there is work on using deterministic Ethernet for control networks, that method does not work across multiple network administrative domains. PMU networks attempt to alleviate this by roughly scheduling samples and by time stamping the actual sample messages (usually using GPS-derived timing); this is fine for non-real time analytics but is problematic for closed loop control, where real time loop dynamics are of critical concern. The concepts of latency margin and jitter margin are useful[42] for real power grid closed loop controls.

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

In general, such closed loop control can be expanded to include integrated control for a wide range of power electronic and other power flow control devices:[43]

- Static VAR Compensators
- STATCOMs
- UPFCs
- Energy storage systems
- DC converter interfaces
- Variable Frequency Transformers
- Static capacitor and reactor banks

Specification 8 details:

8.1 Employ streaming PMU data to provide feedback for closed loop control for stabilization via power electronics devices such as UPFC and FACTS.

8.2 Provide for interaction between the stabilization control and the communication network so that they may be controlled jointly to ensure control loop stability in the face of varying communication network conditions such as latency shifts and congestion.

8.3 Treat communications parameters (latency, jitter, packet loss, routing) and controller parameters (compensator settings, control update rate) as degrees of freedom to be considered simultaneously to determine loop operating settings. In the case of service provider networks, it may not be possible to alter network performance, so use the SDN interface to obtain network performance information that can be used to tune stabilization controller parameters.

8.4 Use similar structure for other forms of closed loop control such as Volt/VAR regulation and frequency regulation via attached services devices and embedded power electronics devices.

[43] E Udren, Wide Area Monitoring and Control, Protection, Automation, and Control World Conference, Dublin, Ireland, June 2010.

Specification 9: Data Flow Models

The specification of the data architecture includes guidelines and constructs that govern the way in which data is collected and processed, how and where it is stored, integrated and exchanged, and the forms of its use in providing resilient operations in the grid. We describe the specification in the context of the structural components in the architecture. While this document specifies the key data flows and data architecture guidelines applicable to BPS, the design-time data models for particular instantiations of the data processed in the grid are to be established during the design of the particular instantiation of the grid. (Those detailed designs start with a conceptual data model focusing on build entities and their relationships, evolving into concrete data models for data communication and management in the form of data stores, and eventually to physical data models.)

Figure 40 shows data flow for structure management in today's grids.

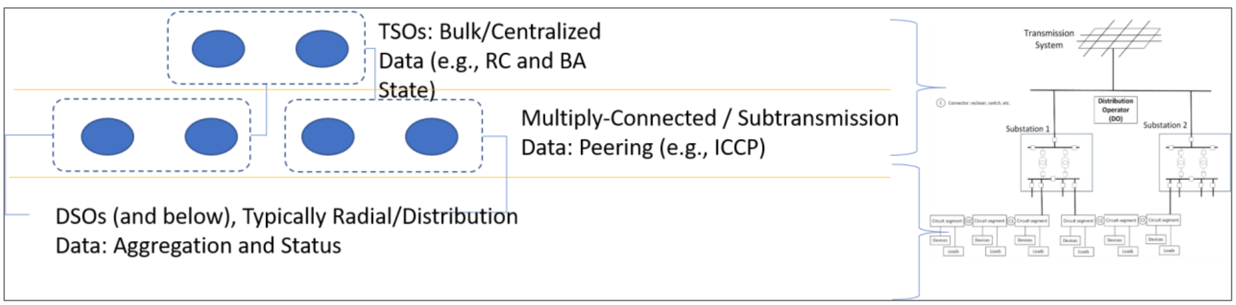

Figure 40 Data Exchange for Today's BPS As-Is Structures

To enable the BPS construction as described in this specification, the data flow architecture maps to the manner in which the TSO treats the T/D connection as a combination of load point and generation tie (as described in Specification 1 in this document). While the TSO is responsible for the data management and exchange for system balance and interchange, it limits its data and state observability up to the T/D interface. This is illustrated in the middle layer of Figure 40 above. The DSO manages the data and state exchange to manage the distribution systems (including DER devices and aggregators).

The BPS architecture that accommodates modern electric grid structures (discussed in Specification 2 in this document) requires data to be held in both a centralized fashion for TSO operations, but also in a more distributed fashion at the TOs and even more distributed when individual PFCs and network of PFCs (especially at large penetrations) must coordinate with each other. For this to happen effectively, a data flow structure such as the one illustrated in Figure 41 is required to operate the BPS to manage new degrees of freedom.

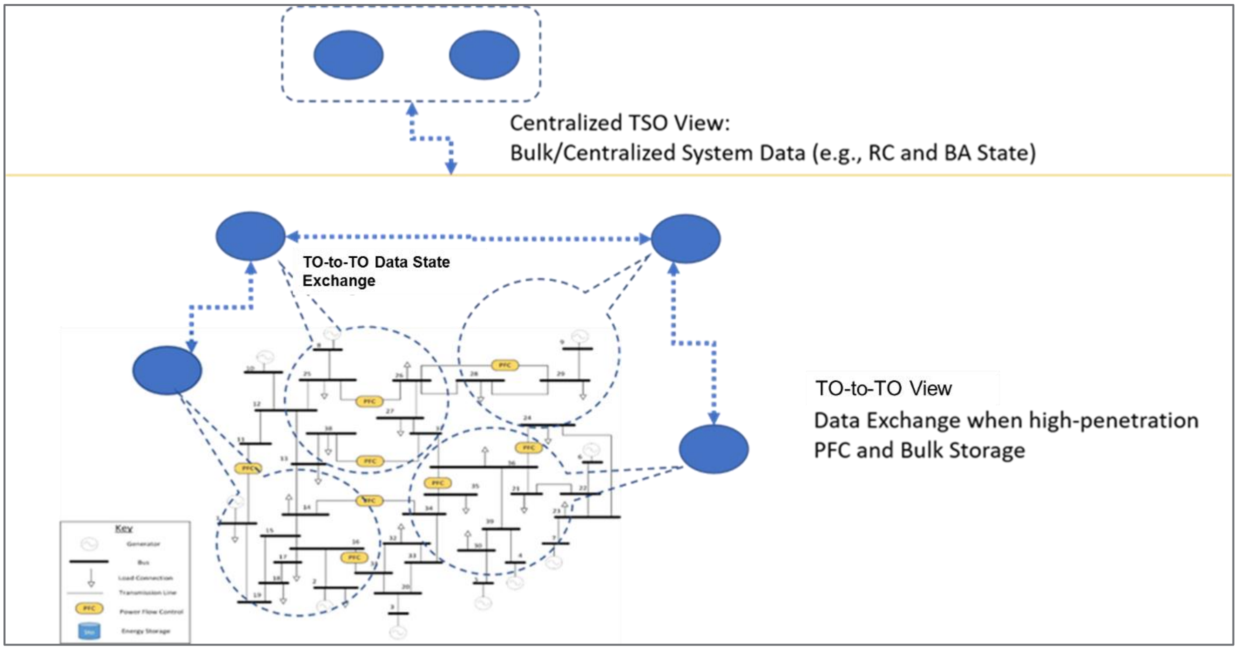

Figure 41 Data Exchange for High-Penetration PFC and Bulk Storage Grid Architectures

This mode of accommodating variable structure in the grid in the form of adaptive power routing and control with PFCs and buffering through bulk storage requires modified data flow requirements compared to existing grid architectures. The data flow must be supported by peering of data elements that communicate control and coordination information for new structures that are permitted in the grid. These permitted structures must be accompanied by continuous monitoring and control and state-space evaluation – not dissimilar to contingency analysis – so that only certain power control operations are permitted. (This prevents arbitrary autonomous behavior which will not support reliability goals of the bulk power system.)

This data flow configuration also applies to BPS structures such as transmission substation networks (discussed in Specification 3.3 earlier) and buffering and energy storage structures in the BPS (discussed in Specification 5). For bulk storage configurations such as the Distributed Storage Control Flat model, the system architecture must support peering of data directly for control and coordination. However, for the Layered Storage Control DSO model, the data exchange requirements are similar to the data interface between the traditional TSO and DSO. For the tertiary mode of fully autonomous operations of bulk storage, the storage service must support a local data store and control that can peer with other components of the grid to return to connected operations.

The structural correspondence of multiple (potentially autonomous) PFC-managed sub-grids, and Storage systems are constituted as LENs that provide the layering discussed in Specification 5. This is illustrated in Figure 42. Data is stored locally to enable the laminar domain operations as described earlier in the Specification 3 (Wide Area Synchronized Sensing and Communications Layer). Support for disconnected and autonomous operations control must be explicitly implemented. This requires computing and data middleware with built in redundancy for data communication failures and explicit operation modes with only partial state. In the figure, the TSO operations and control centers data module is mapped to a data flow module 3.1 (LEN Peering and Bulk Coordination). We show the sub-components that hold the data and state information in module 2.1 (LEN Layering Data State for Cooperative Control and Coordination) and in module 2.1.1 (Distributed State and Control Information for Autonomous Storage and PFC networks). This data process synchronizes state periodically with the peered structures (e.g., PFC controlled transmission sub-networks, or Bulk Storage networks) as laminar domains and sends feedback control signals that are derived from the state data. The support of communication messages and signals that exchange topology and control information are fundamental to the degree of autonomy and peering the sub networks in the BPS are given and when they are incorporated back into broader DSO and TSO operations.

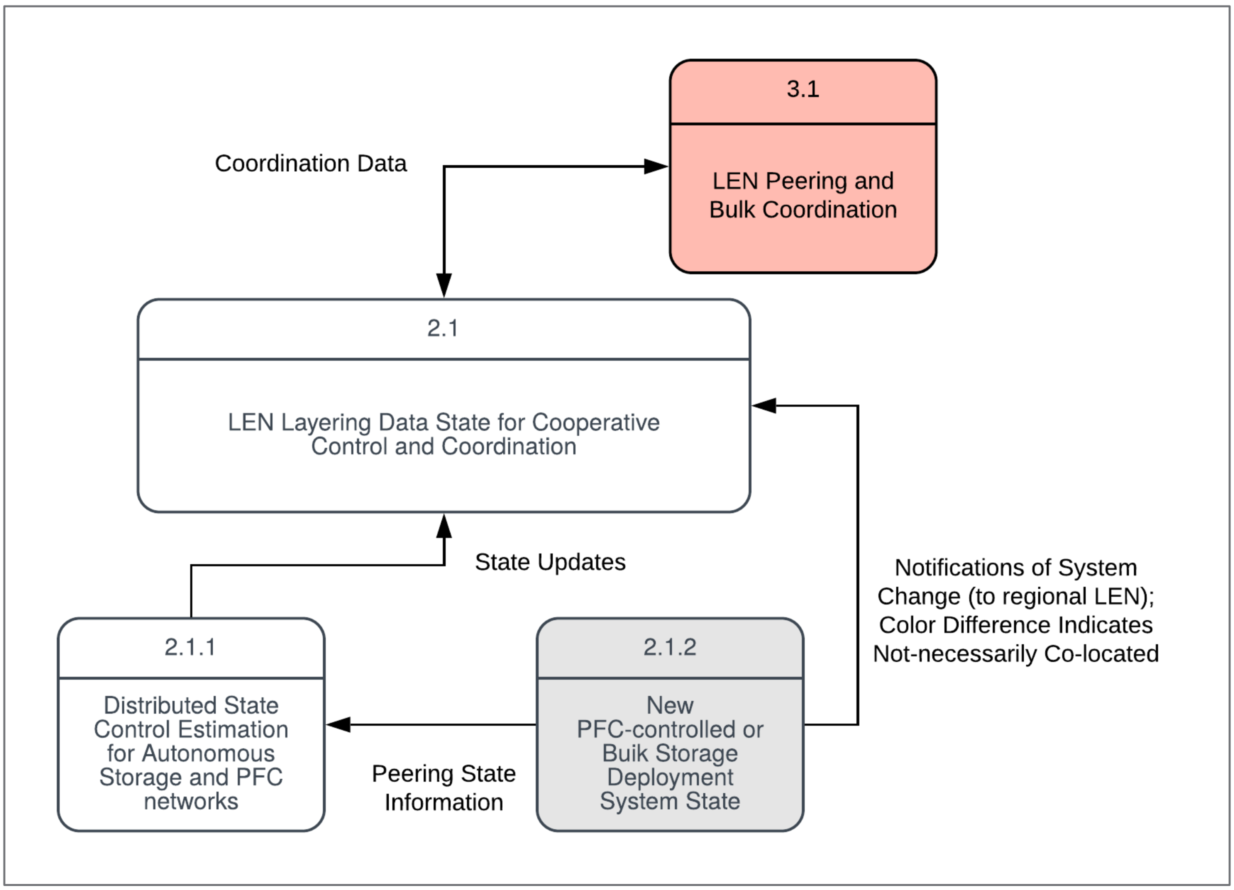

Figure 42 Coordination and Collaboration Data Flows with Bulk Storage and PFC Controlled Sub-networks

To address this issue, data processes must be developed to incorporate system state change (Shown in block 2.1.2 in Figure 42) and these notifications should be exchanged with the local LEN and coordination control networks that enable LENs (e.g., for Bulk Storage) to connect with each other and other parts of the BPS. This data flow construct must be implemented to offer cross-observability in cases of converged infrastructures such as the gas-electric converged architecture (Specification 6).

Specification 9 details:

9.1 Ensure that data observability and management for the BPS is offered as a centralized view for the TSOs.

9.2 High penetration bulk storage and variable structure through PFCs must have a networked, eventually consistent distributed data view. A data flow service for eventual consistency must be implemented. (The needs for this are defined by the control coordination method implemented based on the technology in use.)

9.3 Distributed data stores must be accessible to the centralized view at a defined frequency that supports the reliability requirements.

9.4 The locus of laminar coordination must store the data using established state information gathering and control methods.

9.5 The data service interface must be addressable in a uniform manner. In this regard, the location for a data service for state information retrieval must be available at the TSO, TO, DSO, and LEN levels.

9.6 The data flows must support the same interface for flexible configuration of laminar domains within the domain and for external requests.

9.7 Data flows must support streaming rates for wide area closed loop control (discussed in Specification 8). Data sources should submit data, and data should be held and made available within required time constants for the correct implementation of distributed control, stress resistant, and strain tolerance algorithms deployed in the resilient grid. Ensure that timing distribution dependencies are explicit.

List of Attached Documents and Reference Papers

Document Name/File Name	Description	Version/Date
Problem Domain Reference Model – GMLC1.2.1-v2.pdf	Problem Domain Reference Model white paper	Jan 2019
Entities.Definitions.01.09.2019.xlsx	Entities Definitions	March 2019
CA focused industry structure model ER.vsd	California industry structure model (focus on CA ISO service area):	March 2019
New York: *NY Industry Structure Diagram_v1.2.vsd* and *NY Industry Structure Diagram_v1.2.xlsx*	NY Industry Structure Diagram	March 2019
ERCOT Industry Structure Diagram_v1.xlsx and ERCOT Market Control_v0.1.vsdx.	ERCOT Industry Structure Diagram and Market Control Process Diagram	March 2019
Pacific Northwest: PNW Industry Structure Diagram_v1.xlsx & PNW Industry Structure Diagram_v1.vsdx	PNW Industry Structure Diagram	March 2019
Grid Architecture Component Class Specification – Microgrid v0.1.docx	Grid Architecture Component Class Specification Microgrid	Feb 2019
Grid Architecture Component Class Specification – Power Flow Controller.docx	Grid Architecture Component Class Specification Power Flow Controller	July 2018
Grid Architecture Component Class Specification – Digital Communication Network.docx	Grid Architecture Component Class Specification Digital Communication Network	Sep 2017
Nat gas LMP.pdf	Locational Marginal Pricing of Natural Gas subject to Engineering Constraints – Rudkevich and Zlotnick	2017
Gas-grid_architecture_final.pdf	Grid Architecture At The Gas-Electric Interface - LANL	May, 2017
TPSN.pdf	Timing-sync Protocol for Sensor Networks – Ganeriwal, et al.	Nov., 2003
B5_PS1_Q1.5_UDREN 11Aug2014.pdf	Future Of Distance Backup Zones In A Synchrophasor-Based Wide-Area Backup Protection System - Udren	Aug., 2014
Eric Udren – Synchrophasor-based Wide Area Backup Protection System – iPCGRID 2019(1).pdf	Synchrophasor-Based Wide-Area Backup Protection System - Udren	March, 2019
Adv BPS Ref Arch Drawings 1.1.vsdx	GMLC 1.2.1Grid Architecture Advanced Bulk Power System Reference Grid Architecture V1.1	Oct 2019
InteropStrategicVision2017-04-11.pdf	Interoperability Strategic Vision: Enabling an Interactive Grid – Widergren, et al. DRAFT	April 2017
The Use of Grid Storage for Resilience and Grid Operations final_PNNL.pdf	The Use of Embedded Electric Grid Storage for Resilience, Operational Flexibility, and Cyber-Security O'Neill, Becker-Dippmann, Taft	Oct 2019

Version History

Action	Date	Description	Author(s)
Created	9/25/2019	Originated as the 1.2.1 variable structure architecture specification top level document	GMLC 1.2.1 team
Draft final	11/11/2019	Sections completed	GMLC 1.2.1 team

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