Grid Architecture Specification

February 2019

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Grid Architecture Specification

View Designation: GMLC 1.2.1 High Resilience Reference Grid Architecture

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
	Analytics/Visualization	x	Control/Coordination		Protection
x	Communication Networks	x	Timing Distribution		Cyber-Security
x	Component Class Specification		Component Allocation Model		Grid Dynamics
	Market-Control	x	Computation Resources		Other (name it)

Summary Overview

This document describes architectural (structural) elements for a high resilience electric power system. The architectural concepts are based on a definition of grid resilience and compact theory of grid resilience developed for Grid Architecture purposes.

Glossary

BES – Bulk Energy System

BMS – Building Management System

C&I – Commercial and Industrial

C37.238 – Precision Timing Protocol Profile for the Power Industry

DO – Distribution Operator

DSO – Distribution System Operator

DER – Distributed Energy Resource

DG – Distributed Generation

DS – Distributed Storage

DSN – Distribution Storage Networks

EMP – Electromagnetic Pulse

E-R – Entity-Relationship

ESO – Electricity System Operator

FAN – Field Area Network

GIC – Geomagnetically-Induced Current

GPS – Global Positioning System

NAN – Neighborhood Area Network

ICT – Information and Communication Technology

IoT – Internet of Things

ISO – Independent System Operator

LEN – Logical Energy Network

NERC – North American Electric Reliability Corporation

FCAPS – Fault, Configuration, Administration, Performance, Security

FERC – Federal Energy Regulatory Commission

FLISR – Fault Location, Isolation, and Service Restoration

G&T – Generation and Transmission

PFC – Power Flow Controller

PMU – Phasor Measurement Unit

SOA – Service Oriented Architecture

PTP – Precision Timing Protocol (IEEE 1588)

PTP TC – Precision Timing Protocol Transparent Clocks

PTP BC – Precision Timing Protocol Boundary Clocks

T/D – Transmission/Distribution

TEDS – Transducer Electronic Data Sheets

TSO – Transmission System Operator

ULS – Ultra Large Scale

V/VAR – Volt / Volt Amperes Reactive

WAN – Wide Area Network

XMPP – Extensible Messaging and Presence Protocol

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.

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*.

Scenario and Point of View

The reference model scenario set for this reference architecture is contained in the document *High Resilience Reference Architecture Scenarios.pdf.*

The point of view in this reference model is multi-structure systemic across multiple industry structures and regions.

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* and *PNW Industry Structure Diagram_v1.xlsx*.

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*.

Objective

As described in the reference document **Grid Architecture 2**,[4] modernized grids must support seven system Qualities, namely Delivery, Conservation, Preservation, Protection, Adaptivity, Enablement, and Merit. Collectively, these Qualities encompass the issue of resilience. Specifically, the objective for this reference architecture is to modify existing grid structure and specify new grid structure as appropriate to improve inherent (structural) grid resilience, where structural resilience for the grid is defined broadly in terms of stresses and failures but is delimited to focus on structure, as opposed to processes. Figure 1 illustrates the domains resulting from the definition.

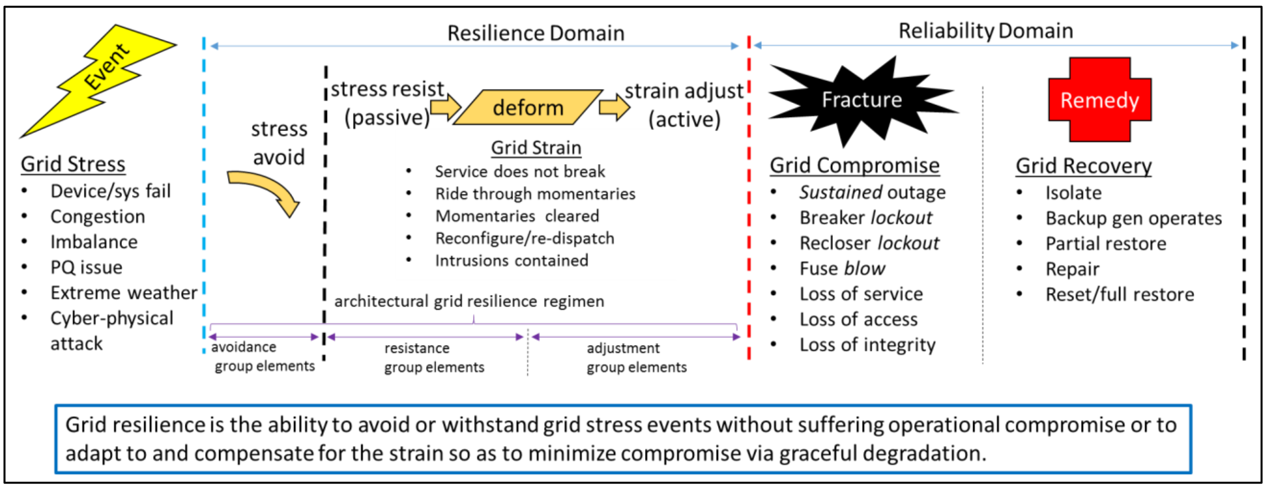

Figure 1 Grid Resilience Definition

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

- Improve grid resistance to stresses
- Improve grid strain adjustment capability

The structural changes should be as limited as is feasible and should be implementable in incremental or proportional fashion without the need to disable large portions of the grid or to disable any part for significant time periods. To the extent that the grid structural changes can enable, support, or provide potential to improve recovery after some failure, they should also do so.

Core Resilience Architecture Principles

1. Grid resilience is the ability of the grid to avoid or withstand grid stresses without suffering operational compromise or to adapt to and compensate for the resultant strains so as to minimize compromise via graceful degradation. Grid resilience should be understood in terms of grid vulnerability, not in terms of hypothetical large rare events. Resilience elements comprise countermeasures to grid vulnerabilities.

[4] JD Taft, Grid Architecture 2, PNL-24044 2, January 2016, available online: https://gridarchitecture.pnnl.gov/media/white-papers/GridArchitecture2final.pdf

2. The resilience domain has three regimes: stress avoidance, stress resistance, and strain adjustment. The scope of resilience includes more than just device/system failures and large exogenous events; it includes stressors related to operational issues and non-circuit exogenous forces.[5,6]
3. Grid resilience architectures use the following as foundational elements:
   3.2. Situational awareness (monitoring, forecasting, extended grid state)
   3.3. Planning/design for resilience
   3.4. Interoperability & interface standards
4. Grids are Ultra Large Scale systems, subject to normal failures.[7] Consequently, architecture should not treat failures as exception conditions but as part of normal operating modes.
5. The architecture views should employ redundancy/critical component backup to eliminate single points of failure and to provide options for strain adjustment.
6. The architecture views should incorporate buffering for the purpose of decoupling volatilities that may be induced by stochastic generation sources and the behaviors of controllable loads.
7. The architecture views should make use of modularity principles, namely module strength and module (de)coupling, to limit propagation of stresses and strains and therefore cascading failures.
8. Dependencies should be minimized to limit system brittleness (anti-resilience).[8] This may involve decoupling or may involve structures that provide some form of compensation for dependency, such as resilience loops in gas-electric systems.[9]
9. The architecture views should use structures that enable agility, adaptation, and configurability (including energy resource flexibility) to support strain adjustments. This is related to redundancy and modularity.
10. Architectural views should provide structures that can support or enable graceful degradation[10] in the event of grid strains.

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[5] JD Taft, Electric Grid Resilience and Reliability for Grid Architecture, PNNL, March 2018, available online: https://gridarchitecture.pnnl.gov/media/advanced/Electric_Grid_Resilience_and_Reliability_v4.pdf

[6] S Widergren, A Shankar, B Kelley, R Melton and J Taft, Toward a Practical Theory of Grid Resilience, GMLC, April 2018, available online: https://gridarchitecture.pnnl.gov/media/advanced/Theory_of_Grid_Resilience_final_GMLC.pdf

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

[8] A brittle system is characterized by a sudden and steep decline in performance as the system state changes. A system is brittle if it is unable to effectively absorb stress-induced shock.

[9] See for example JD Taft and A Becker-Dippmann, Grid Architecture, PNNL, January 2015, Section 6.2 Electricity/Gas Interaction, available online: https://gridarchitecture.pnnl.gov/media/white-papers/Grid%20Architecture%20%20-%20DOE%20QER.pdf

[10] Graceful degradation is the ability of a system or network to maintain limited functionality even when a portion of it has been rendered inoperative. In graceful degradation, the operating efficiency or speed declines gradually as an increasing number of components fail. It is somewhat analogous to ductile failure in materials.

11. Architectural views should provide structures that can support or enable fault tolerance[11] in the event of stress-induced failures.
12. Known resilient structures (distributed systems, layering, platforms, etc.) are to be preferred where appropriate.

Core Architectural Concepts

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

All hazards approach – resilience is not limited to selected large, rare events or cyber-attacks. All forms of stress on the grid and it component elements is considered, including those arising from processes such as software upgrades, operator/configuration error, and device mis-calibration.

Situational awareness – the need for situational awareness is taken as 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.[12]

ULS normal failures approach – applying Ultra-Large Scale system theory to the grid leads to the view that faults and faults must be treated as normal events rather than exceptions. Architectural structure should be selected to mitigate the impact of such failures in the same way as with other grid stresses. In other words, *the ultra-large scale complexity of the grid is a source of grid stress.* 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.

System hardness – hardness for grid resilience purposes usually associated with components and this is addressed below in this reference architecture. In addition, it is useful to consider the "hardness" of subsystems and whole systems to identify structural weaknesses and determine structural improvements that affect structural hardness (the ability of a grid structure to withstand stress).

Flexibility – 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 also 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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[11] Fault tolerance is the property that enables a system to continue operating properly in the event of the failure of (or one or more faults within) some of its components. A highly fault-tolerant system may continue at the same level of performance even though one or more components have failed.
[12] 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

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. The platform structure mentioned earlier is an example of such a foundation.

Agility – the speed with which either flexibility or extensibility can be exercised.

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.

The distributed architecture concept is applied to the grid in several ways. The most obvious is for coordination and control, but also applies to generation and storage, and to data management and analytics (intelligence). Note that markets are always distributed systems, even when the market clearing mechanism is centralized, as is the case with organized wholesale electricity markets.

Buffering – most complex systems have buffers of one kind or another. Communications systems use jitter buffers to even out the flow of data bits from uneven sources. Logistics systems use buffers – they are called warehouses. Water and gas systems use buffers – they are called storage tanks. In each case the buffer serves to even out flow variations. By acting as a kind of shock absorber, by providing springiness or sponginess, they cushion a system against stresses due to volatility of sources. Such springiness gives the system resilience. Lack of buffering is a vulnerability.
Power grids (especially at the distribution level) lack buffering, due in part to limitations on technology and for the distribution case, due to lack of a need for it in the 20th Century. Buffering addresses resilience vulnerability in a number of ways, including even to some forms of cyber-attack.

Structural resilience – architectural structures may be more or less resilience due to intrinsic characteristics. Identification of structural resilience vulnerabilities in legacy grid structures and determination of minimal changes to structure to address those vulnerabilities is a key aspect of Grid

Architecture work. Structures and structural principles whose resilience properties are known to be strong include:

- Layering and platforms, including structures derived from layered decomposition
- Core/edge network structure
- Modularity and (de) coupling

Modularity bears a strong relationship to interoperability in that modularity requires clear interface definitions and those interface locations and definitions derive from architectural structure and from basic module characteristics such as module strength and module coupling.

The grid structures to be treated in terms of structural resilience include:

- Industry and market structure – tier bypassing, scaling, and cyber security are key issues
- Electrical (circuit) infrastructure – coupling and hidden coupling are key issues
- Controls – hidden coupling, scaling, latency, fault tolerance, and cyber security are key issues
- Information systems and communication networks – brittleness via coupling and cyber security are key issues
- Converged networks (such as gas/electric systems) – dependency is a key issue
- Coordination frameworks and structures – fault tolerance, extensibility/flexibility, and scaling are key issues

Redundancy – avoidance of single points of failure is structural approach to system resilience. In this regard, a “point” may be a single component, or may be a whole subsystem, such as a communication network. Redundancy may involve the use of multiple components that can serve the same function but may not be implemented identically. An example would be the use of two communication systems that employ different physical media (optical fiber and microwave for example) to carry the same data traffic between the same endpoints. It may involve backup components that are technologically different from primary components, such as the case where primary relays are digital but backup relays are electromechanical. Structurally, it may involve redundant pathing, such as for electric circuits with more than one available path configuration or communications systems with physically separates paths (separate optical fiber physical layout routes, for example).

Architecture Specifications

The architectural views are presented in terms of (black box) components, structures, and externally visible characteristics.[13] 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 – Fuel Stockpile

Grid Architecture Component Class Specification – Storage v0.2

Grid Architecture Component Class Specification - Middleware

Grid Architecture Component Class Specification – Microgrid v0.1

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.

Grid Energy Storage as a Resilience Component

Grid energy storage is available in a variety of forms with a range of values of the externally visible properties. See *Grid Architecture Component Class Specification – Storage v0.2* for a list of key externally visible properties.

While some models for the use of grid energy storage are based on the concepts of value stacking of multiple functions and monetization of storage by bidding grid services into wholesale markets, there are a number of used for grid energy storage that serve to improve grid resilience. These generally fall into the functional category of volatility decoupling in line with principles 6 and 7. Principles 10 and 11 come into play as well by providing power loss ride-through. When applied at the distribution level, such decoupling is bidirectional, meaning that volatility arising at the Bulk Energy System (BES) level can be decoupled from the distribution system and loads; volatility at the distribution edge arising from DER can be decoupled from the BES. There are resilience advantages to both types of decoupling. Generally, the use of grid energy storage at the electric distribution level as a resilience component relates to a range of operational functions, as opposed to BES grid services.

These operational functions include:

- Regulation and Stabilization
- Outage Ride-through

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

- Black Start Support
- Volatility Management
- Distribution Flow Management Support
- System Integrity Remediation
- Mitigation of the Need for Secondary Load Control

<u>DER as a Grid Resilience Component</u>

Distributed Energy Resources have the potential to enhance grid resilience when present insufficient quantity in line with principle 9. We include distribution-connected generation, storage, and demand response in the term DER, so there is a mix of capabilities, time scales, etc. included in this generic component type, meaning that care must be taken when considering how to use DER for any particular purpose. At sufficient penetration, DER transforms distribution systems into something that acts less like a dependent aggregated load and more like a hybrid of load and a generation tie point. The essential underlying change is structural and has happened largely organically. However, to make use of DER as a resilience-enhancing component type, structural changes to the grid are useful or even necessary.

In particular, the relationship between transmission operation and distribution operation, involving coordination, control, and communication, should change to address the tier bypassing and distribution observability problems. The necessary structural changes are at the root of the discussions about Distribution System Operators and are addressed in the specifications below.

<u>Fuel Stockpiles</u>

Fuel stockpiles are important grid components but are **not** examples of grid energy storage. This issue is not whether fuel stockpiles have energy stored in them (of course they do), it is whether the energy came from the grid before it was stored. Consequently a generator plant coal pile is not grid energy storage.

In terms of grid resilience, **fuel stockpiles are buffers** in the logistical sense. They decouple incoming supply flow of fuel (on a train or barge, say) from use of fuel at the generator. In that sense, fuel stockpiles are resilience elements and they serve to enhance the ability of the grid to avoid stress as follows: interruptions in fuel delivery could place stress on the grid by causing loss of generation but a fuel stockpile could avoid that stress by keeping the generators running until the fuel flow is restored. In other words, fuel stockpiles provide ride-through for interruptions in the supply of fuel to generators. This is an essential resilience function: *fuel stockpiling is a form of buffering*, even though it is *not a form of grid energy storage*. As such, it can be a valuable grid resilience measure and should be considered as part of an overall resilience strategy, in line with principles 5, 6, and 8.

<u>Component Hardening</u>

Grid Architecture is largely concerned with *structure* as opposed to components but in the case of grid resilience, component hardening has an important role in <u>stress resistance</u>. This includes standard issues such as hardening utility poles, placing circuit components underground or above ground as the case may be, or securing substation gear against physical attack with metal plates, etc. It also includes more esoteric issues such as protecting substations against Electromagnetic Pulse (EMP) or Geomagnetic Induced Currents (GIC) via shielding or other means,[14] and making electronics equipment able to withstand electrical transients, thermal shock and expansion/contraction, moisture and salt fog, wind sway, attack from rodents, reptiles, insects and arachnids, and resistance to facility break-ins.

Component hardening is not a structural (in the Grid Architecture sense) issue so much as it is an engineering issue. By and large, electric utility engineers know which grid components to harden and vendors and contractors know how to do the hardening. Grid component hardening is more a matter of resilience strategy and financing.

System hardening can be architectural issue to the extent that grid resilience can be improved via structural modifications and is addressed below.

Low Technology Components

Some aspects of vulnerability of the grid have roots in the use of high technology components (typically involving electronics, software/firmware and communications capabilities). One approach to addressing these vulnerabilities is to revert to the use of less technologically advanced components, such as analog instead of digital protection relays. This is also more an engineering issue than an architectural one, but there is a structural consideration in how the low-technology components may be used in a grid: the choice is between the use of such elements in primary systems, or in backup systems. If the choice is to use high tech components in the primary system (to get the functionality) and low-tech components in the backup systems, then it is likely that the communication requirement for the backup systems will be modest to non-existent and in fact it may be that communication to the backup systems may be deliberately restricted or even banned. In such a case, the backup devices must be capable of autonomous operation and cannot explicitly cooperate. The structure of the involved system (for example the protection system) would then be essentially double in form and the primary and backup systems may be isolated from each other except for electrical connectivity (which can be a large exception, not to be discounted, especially in considering cyber vulnerabilities).

If low technology components are used in the primary systems, then it is necessary to revert to the use of people and processes to make up for the lack of automation and communication that has been sacrificed. This is less of a burden if the automation has not yet been applied, but may be problematic if a system is being technologically downgraded.

Structural Resilience Implications of Middleware

Middleware got its start as a means to connect two monolithic software systems running on separate computers. Since these systems had not been developed with the means to share information or processing, special software was developed fit in between them. Later the concept was generalized to

[14] Note that there has been some work on circuit structure for GIC resilience, namely orientation of transmission lines, but there does not seem to be sufficient clear advantage to list this as a resilience structural architecture element.

connect and facilitate cooperation among multiple systems. For the enterprise IT environment in the context of web services and SOA, the evolution of middleware resulted in the development of enterprise service buses. For sensor systems and for emerging IoT systems, middleware has been recast as a platform that provides an abstraction layer capability that separates the sensors and communications from the applications that use it and hides the details of the physical system from the applications. While this is consistent with the layering principle, the underlying structure of actual implementations contains the same structural constraint as the previous version of middleware.

Middleware in this context provides a logical data management layer and is often depicted in a manner that makes it appear to be a distributed structure. In the NASPInet case it can isolate applications from the details of the physical and communication elements of the PMU network. It may supply various services, including pub/sub capability and other data management functions. To accomplish this, the new middleware software is inserted in between the physical system and the applications. The middleware must be hosted on one or more servers and must itself be managed in addition to the other elements of the PMU network. PMU data must flow to the middleware and be redistributed from there.

Drilling down into the platform model a bit more reveals the structure illustrated in Figure 2.

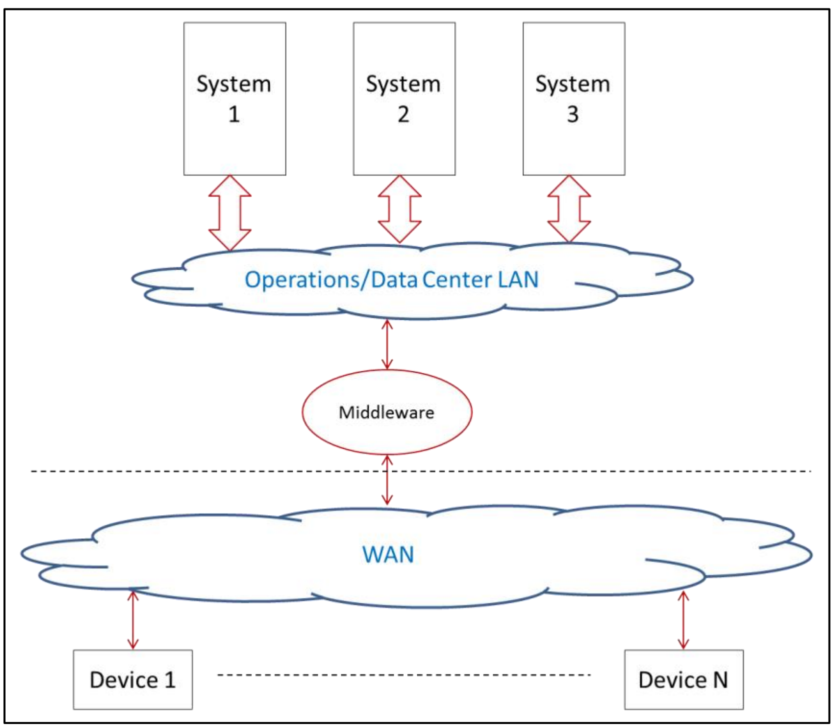

Figure 2 Middleware Structure

The platform middleware resides on a server or server cluster in a data or operations center, whereas the data sources and control elements are distributed throughout the electrical infrastructure in the power grid case. This platform middleware model derives from the basic IoT[15] scenario, which presumes

[15] Internet of Things

the field devices are independent and decoupled. This model does not match the forward-looking electric grid use cases related to closed loop protection and control, as well as potential use of distributed analytics and grid intelligence. Figure 3 illustrates the essential mismatch between the IoT model and the grid model.

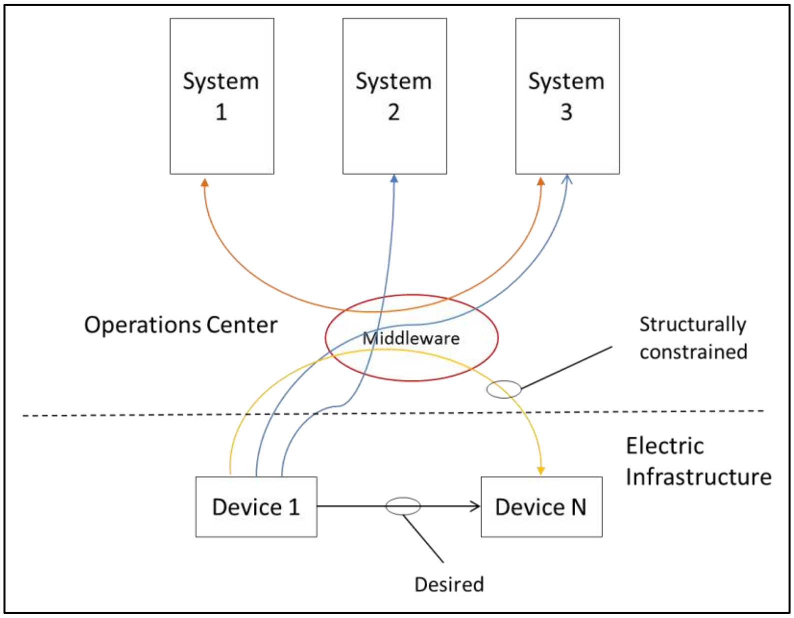

Figure 3 IoT Middleware and Grid Distributed Systems

An essential difference between the IoT and future electric grid models is the need for peer-to-peer data flow. Forcing that flow through a middleware system located at an operations center results in the middleware becoming a bottleneck, a source of excess latency, and a new cyber vulnerability.

The problem here is that while an abstraction layer is helpful from a software standpoint, the underlying structure imposed by the implementation is not appropriate for a system that involves a highly decentralized infrastructure, such as the electric grid. This specification provides a different structure (see below) that makes use of grid resilience principles 8-12.

<u>Structural Implications of FLISR</u>

FLISR[16] is a capability that exists at the border between the resilience domain and the reliability domain. For the aspects of FLISR that operate in the time scale defined per utility as momentary outage, this capability increases resilience according to principles 9 and 11. The use of FLISR has implications for circuit structure and for communications structure. The circuit structure issue comes about due to the need to provide segmentation of circuits and alternate paths for power flow. The communications structure implications come about based on whether the FLISR system control is implemented in a centralized or distributed form and whether DER play any active role.

[16] Fault Location, Isolation, and Service Restoration. This is a capability for operation of distribution primary feeder circuits. Note that fault location implies fault detection, and usually requires fault characterization.

Key Structures

This section provides the architectural specifications for the high resilience reference architecture. It contains three parts:

1. Baseline E-R Model – a representation of the grid as it exists now that defines the starting point for a grid modernization. Some utilities and parts of the overall grid will vary slightly in that some progress on modernization has already happened, but this model provides a baseline that provides context for structural changes specified in the views.
2. Single Structure Views – specifications and representations of individual grid structures, as defined by the classes of the Network of Structures paradigm.[17]
3. Composite Structure Views – specification and representation of a whole grid architecture the combines the single structure views and other elements as needed.

Baseline E-R Model

The diagram in Figure 4 is a baseline structural model for electric power systems, cast in the form of an Entity Relationship diagram. This model includes distribution-connected generation, storage and responsive loads (demand response), collectively referred to here as edge resources. A number of organizational and individual entities are shown although this is not intended to show all (for that, see the industry structure models and the entity list referred to earlier). This diagram is a hybrid that includes entities and systems/devices. The standard electrical infrastructure is on the right in the vertical stack of blue boxes. Primary grid operational entities are shown in green. Non-utility entities are shown in gray and pink. Two sub-structures (microgrid and substation service area) are show in white boxes.

This diagram represents the traditional electric delivery system power flow model (from bulk generation through transmission and distribution to users), but includes DER in its typical present day manifestation. While the proliferation of DER has started to cause structural and operational changes in some areas of the US, actual penetration has by and large not caused utilities to move past the first stage of distribution grid evolution, as defined in the DSPx three stage model,[18] so this schema is a useful "starting point" representation. The specifications below will describe a model reference grid architecture with a focus on structural resilience improvement. That will provide the "ending point" representation.

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[17] J Taft, R Melton, D Hardin, Grid Architecture Overview, PNNL-SA-128082, available online: https://gridarchitecture.pnnl.gov/media/methods/SEPA_Grid_Architecture_Overview.pdf

[18] P De Martini, et. al., Modern Distribution Grid Decision Guide Vol III, July 28, 2017. See Figure 4 on page 15. Available online: https://gridarchitecture.pnnl.gov/modern-grid-distribution-project.aspx

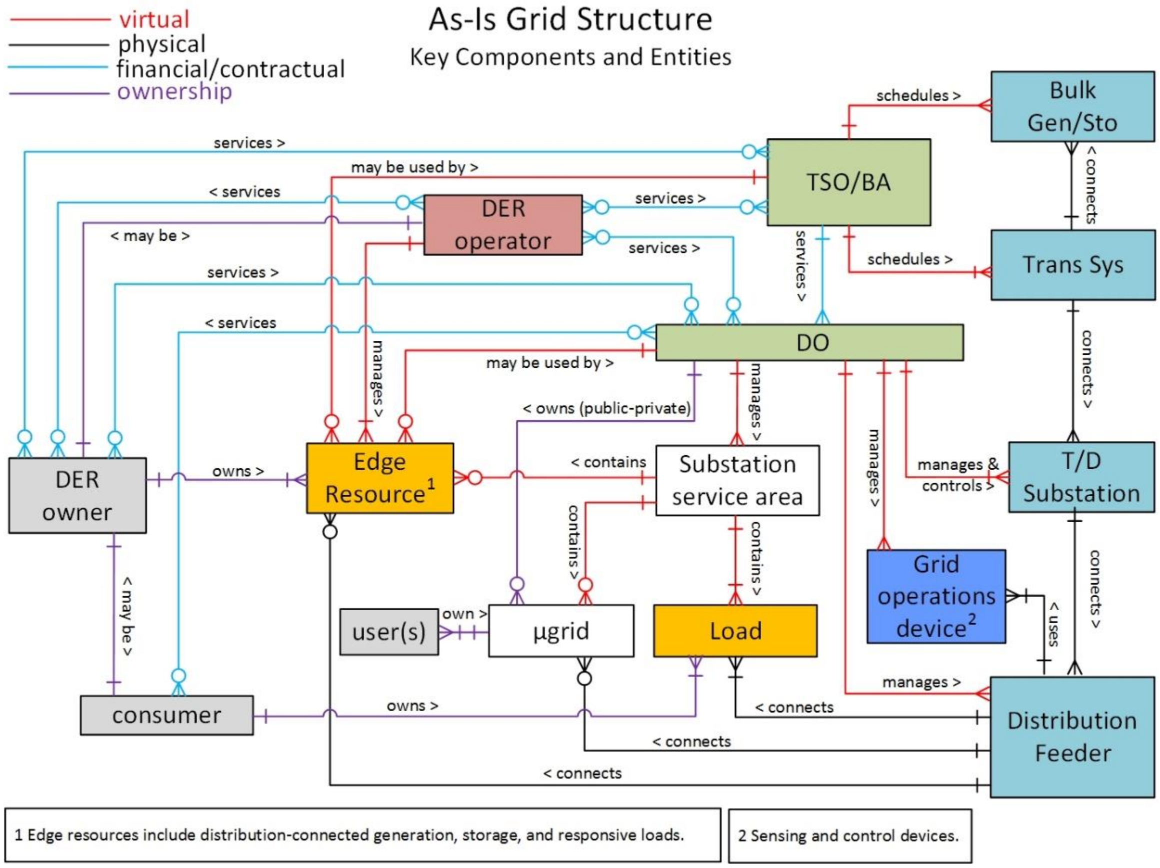

Figure 4 Existing Grid E-R Structure Diagram

The stack diagram in Figure 5 is an alternate representation of the same system. In this depiction, the grid is viewed as comprising two primary domains: the bulk energy system domain and the distribution domain.[19] This model emphasizes the similarities and differences in gross organization structure (not physical infrastructure) will be used to enhance the partial homology[20] that exists now to derive a new structure the enables means to use DER for improved grid resilience. It should be noted that there is little or no operational coordination between bulk system operators and distribution operators. This model reveals structural constraints that must be relieved to simplify the coordination that will be necessary for the use of DER as resilience assets.

[19] See Visio file *high res arch drawings v1.13.vsdx* for extended stack models with non-utility domains (buildings, microgrids, DER).

[20] In the biological sense of structural correspondence.

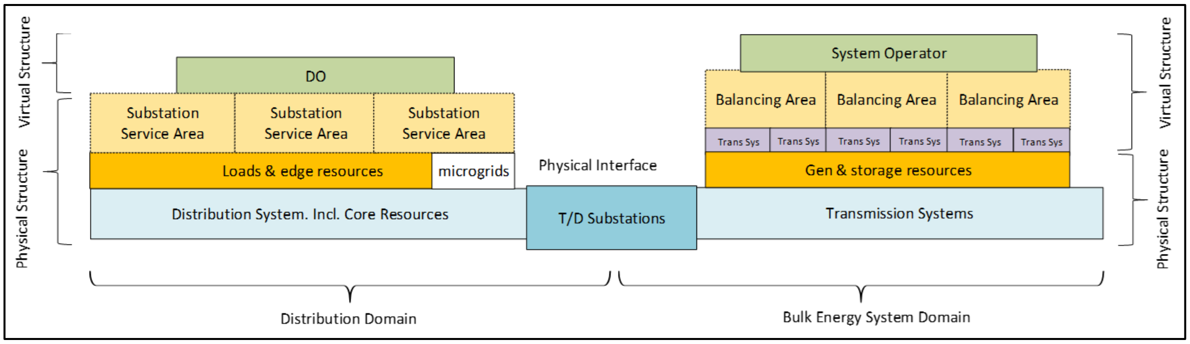

Figure 5 Existing Grid Stack Model

These two representations are a baseline from which some aspects of the high resilience reference architecture representations will be derived, especially as regards electric distribution.

Single Structure Views

This section provides a number of single structure specifications. Each focuses on a specific structure class from the standard set: electric infrastructure, industry structure, ICT superstructure, control structure, converged networks, and regulatory structure. In this specification, regulatory structure is treated only as a constraint. Converged network issues are considered in the section on composite views.

Specification 1: Total DSO/TSO Industry Structure

The purpose of this structure (also called the Market DSO model) is to enable the use of distribution connected assets (DER) for grid resilience 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 6 illustrates the basic DSO/TSO structure.[21]

[21] 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

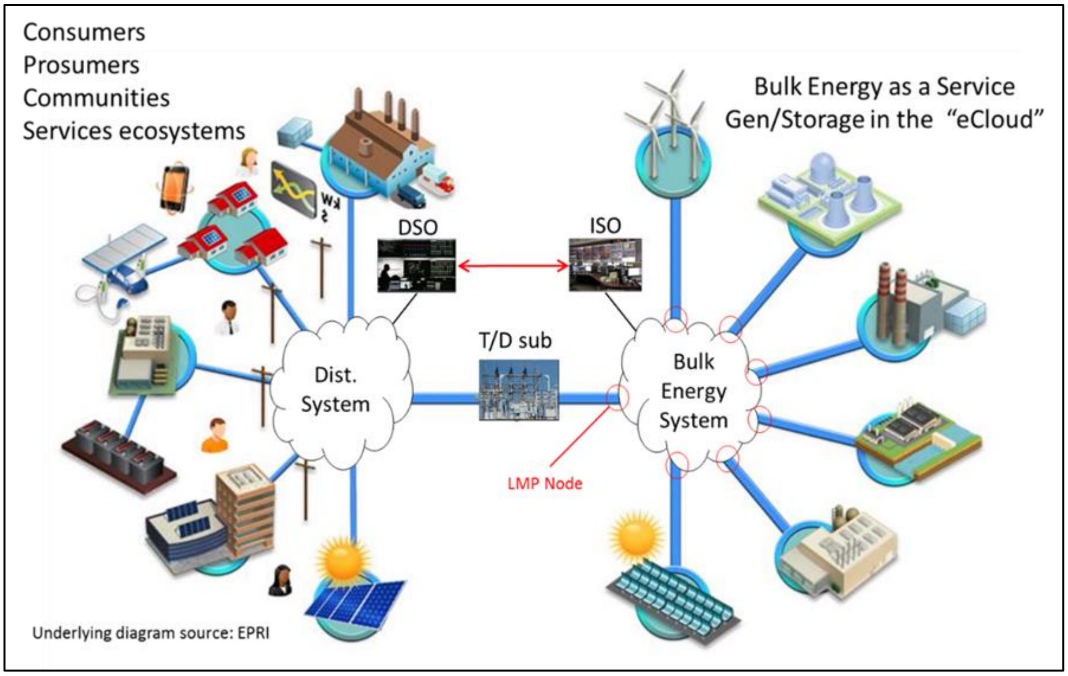

Figure 6 Total DSO/TSO Industry Structure Model

Specification 1 details:

1.1 Distribution providers have a total Distribution System Operator role.
1.2 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.
1.3 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.
1.4 The TSO limits its grid observability to the bulk energy system up to the T/D interface; it does not obtain grid state or operational data from DER devices or aggregators.
1.5 The TSO does not by bypass the DSO to dispatch DER directly.
1.6 DER aggregators and other third party energy services providers do not bypass the DSO to deal directly with the TSO.

A consequence of this specification is that DER telemetry flows and dispatch instruction flows have a structure shown in Figure 7, where the lines indicate bidirectional data flow paths.[22]

[22] 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

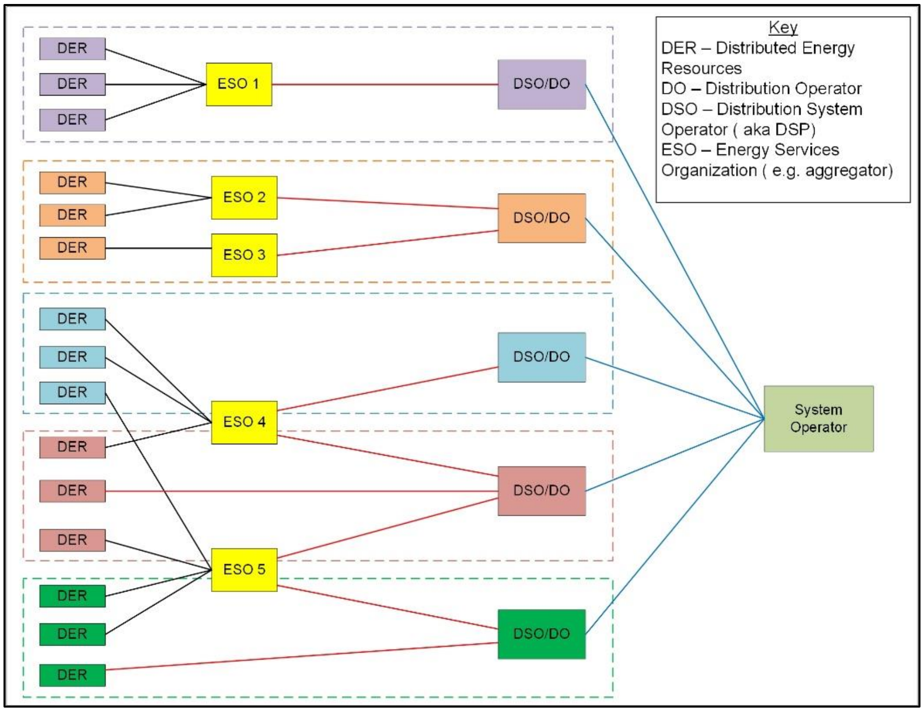

Figure 7 Multi-DSO DER Telemetry Flows

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 "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.

This industry structure introduces a new interface: the DSO/TSO interface (indicated by the red double ended arrow in Figure 6). 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:

a) Forecasts (load, available DER)
b) Bids and clearings
c) Dispatch requests
d) Aggregated distribution grid state, including grid services capacities
e) Grid services requests
f) 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. The DSOs will have interfaces to ESOs and potentially to DERs, depending on how they set up their grid codes (interconnection rules). Each DSO must only handle the DERs and ESOs operating in their respective service areas, which provides some limits on interface and system scaling issues for the DSOs. DSOs may choose to require DERs to interface through ESOs to help contain interface scaling. The potential interpenetration of ESO DER accounts in a given DSO service area represents a complexity but this industry structure combined with another to be introduced later (Laminar Coordination networks) provide a general framework for architectures that manage the scalability issue for operational systems.

Specification 2: Transmission Observability Platform

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). 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 8 illustrates the platform for private communication networks.

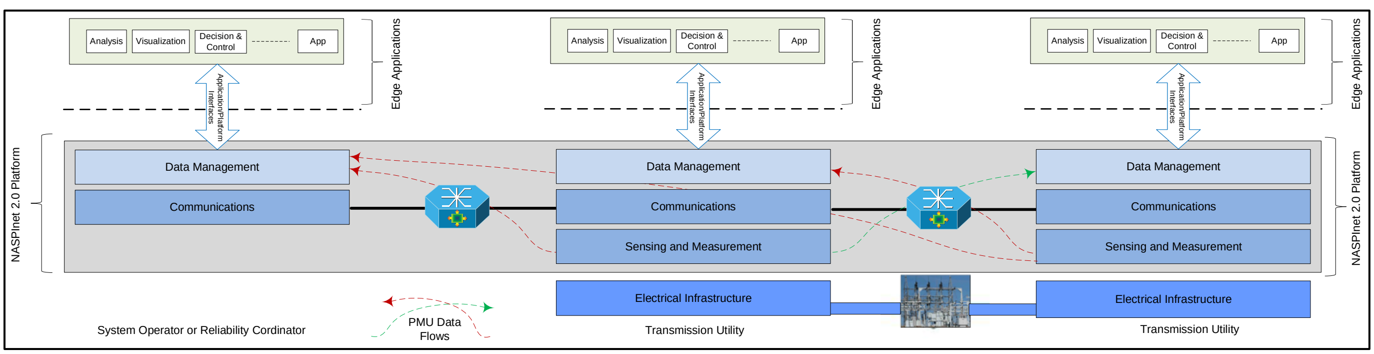

Figure 8 Transmission Observability Platform with Private Networks

Figure 9 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.

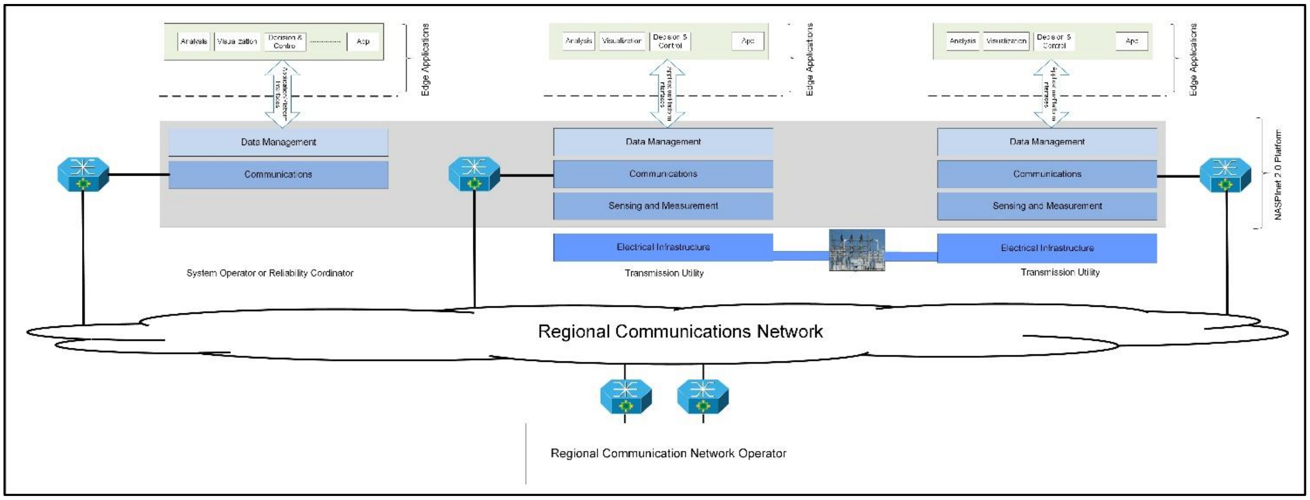

Figure 9 Transmission Observability Platform with Telecommunications Service Provider Networks

The same communication network core-edge principle applies as with the private network version, as do the other guidelines in the NASPInet2 guidance.[23]

Specification 2 details:

2.1 Treat sensing/measurement and communications as an infrastructure layer.

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

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

2.4 Combine the sensing, communications layer, and applications to form a distributed observability platform. Use this platform to manage sensor data flows.

Specification 3: Backup Protection Redundancy

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 resilience, 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 10 illustrates the basic structure.

[23] NASPI, NASPInet 2.0 Architecture Guidance, October 2018 (WIP).

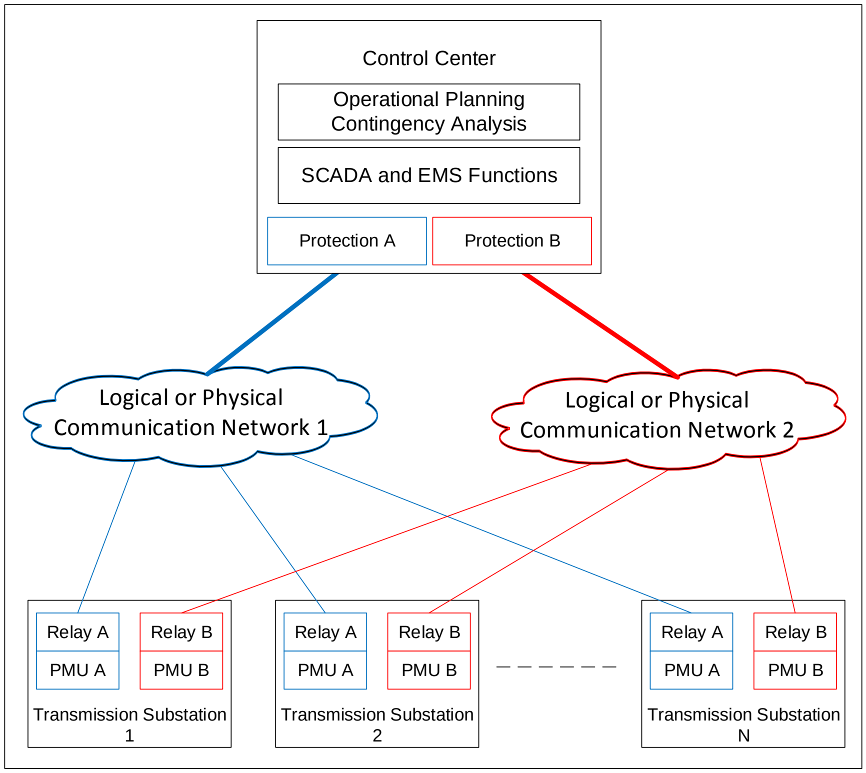

Figure 10 Backup Protection Redundant Structure

Specification 3 details:

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

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

3.3 Use dual redundant relays and PMUs in the substations.

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

Specification 4: Distribution Layer Structure & Observability Platform

The layering and platform concepts are applied to electric infrastructure, sensing and measurement, and communications for electric distribution to define a platform for resilient electric distribution operations. Figure 11 shows a commonly used structure for electric distribution utility sensing and control.

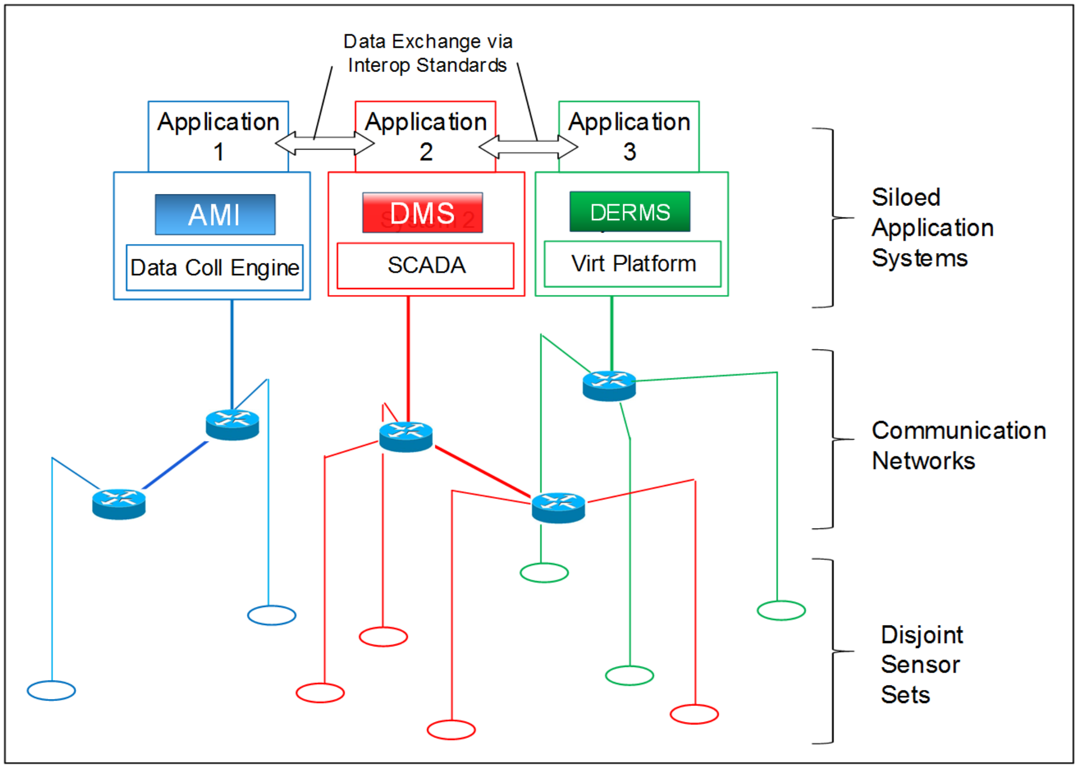

Figure 11 Siloed System Structure

This multiple vertical silo structure is expensive due to back end integration costs, and is anti-resilient due to the back end coupling of applications – failure in one can ripple through to degrade others. It is also anti-extensible, because adding or subtracting applications requires new integration to existing applications. Interoperability efforts have yet to simplify the integration problem and *cannot address the anti-resilience issue, which is fundamental to this structure.*

Figure 12 illustrates the layering and consequent decoupling of applications that limits brittleness and enhances configurability, functional flexibility, and functional extensibility in line with principles 8 and 9.[24]

[24] 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

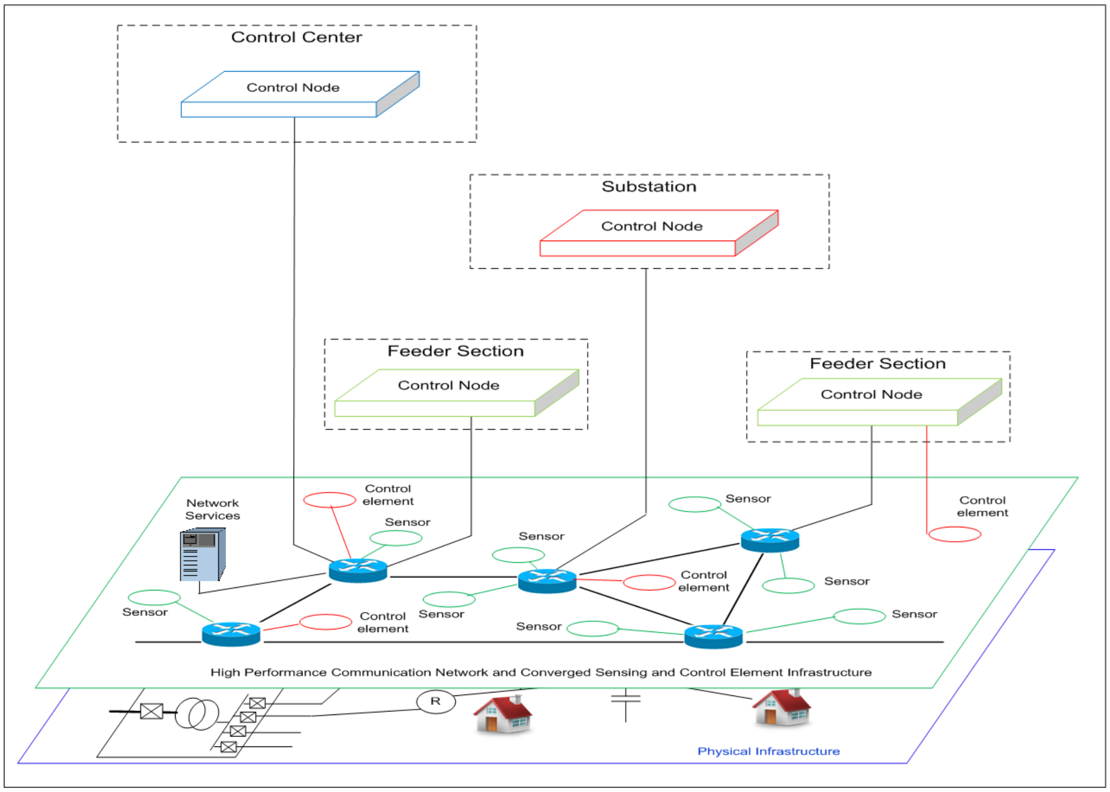

Figure 12 Sensor Communications Layer Structure

Note that this structure significantly changes the locations and nature of interfaces between grid data sources and applications. This structure defines three layers and a distribution platform:

- Layer 1: electric infrastructure
- Layer 2: sensing and communications layer
- Layer 3: application layer

Layers 1 and 2 constitute the platform. In addition to the physical components, the platform provides a set of functions and services that are depicted abstractly in Figure 13.

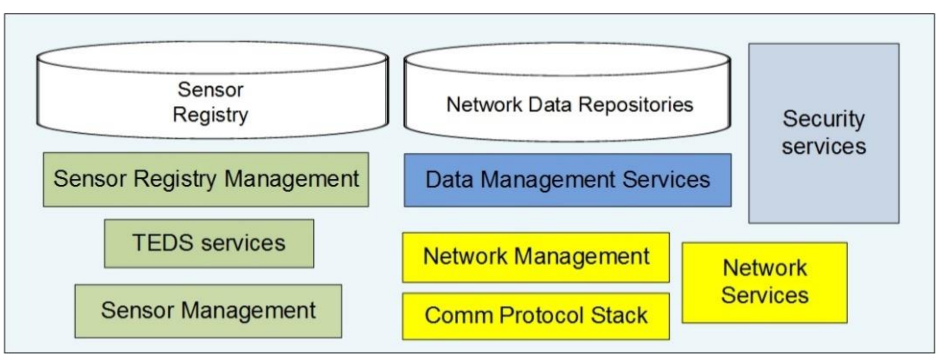

Figure 13 Sensor/Communications Infrastructure Layer Functions

This is a combination of typical communication functions and services, combined with two other items: services for sensors and selected data management services that may be implemented at the communication network level. Network management refers primarily to FCAPS (Fault, Configuration, Administration, Performance, Security) and TEDS[25] refers to Transducer Electronic Data Sheets.

Specification 4 details:

4.1 Treat sensing/measurement and communications as an infrastructure layer.

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

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

4.4 Combine the electric distribution layer and the sensor/communications layer to form a distribution platform. Use this platform with the items from 7.2 to manage sensor data flows.

4.5 Decouple applications (analytics, control, forecasting, measurement & verification) by having each authorized application separately access the platform for the operational data it needs.

4.6 Locate applications as needed, including in operations or data centers, in substations, or in feeder-level devices. Applications may be dynamically relocated.

4.7 Circuit electrical control devices may be included in Layer 2 of the platform.

Specification 5: Distribution Storage Networks (DSNs)

Core resilience architecture principle 6 indicates the use of buffering as a resilience-improving measure. Generally, adding buffering to a system gives it resilience by decoupling volatilities. While some storage exists in electric power systems, electric distribution in particular has little or none. Introducing storage into electric distribution systems as core infrastructure used for resilience and operational purposes (as opposed to energy arbitrage or for bidding grid services into organized wholesale markets). These purposes include generation/load decoupling (including outage ride-through), volatility export suppression, and even cyber-security improvement.[26,27]

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[25] See IEEE 1451.4, available online: https://standards.ieee.org/content/dam/ieee-standards/standards/web/documents/tutorials/1451d4.pdf

[26] JD 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

[27] JD Taft, Defending the Grid from IoT, PNNL-26621, May 2017. Available online: https://gridarchitecture.pnnl.gov/media/advanced/Defending_the_Electric_Grid_from_IoT.pdf

For electric distribution grids, the use of fast bilateral energy storage[28] raises a structural issue, namely how to connect the storage to the distribution system. Going further, it raises the issue of how to operate a collection of distribution-connected storage units as a distributed system for resilience purposes. Since it may not be feasible to put a grid scale storage unit at every distribution substation, storage devices may be shared across more than one substation using distribution feeder level interconnection. As with communication networks, a number of interconnection topologies are possible, including hub-and-spoke, dual hub-and –spoke, loop (ring), and full meshes. Tradeoffs exist in terms of storage unit size vs. interconnection topology for a given level of performance. Choice of interconnection topology is likely to depend on other factors. Figure 14 shows a distribution feeder loop interconnection topology for shared distribution level energy storage.

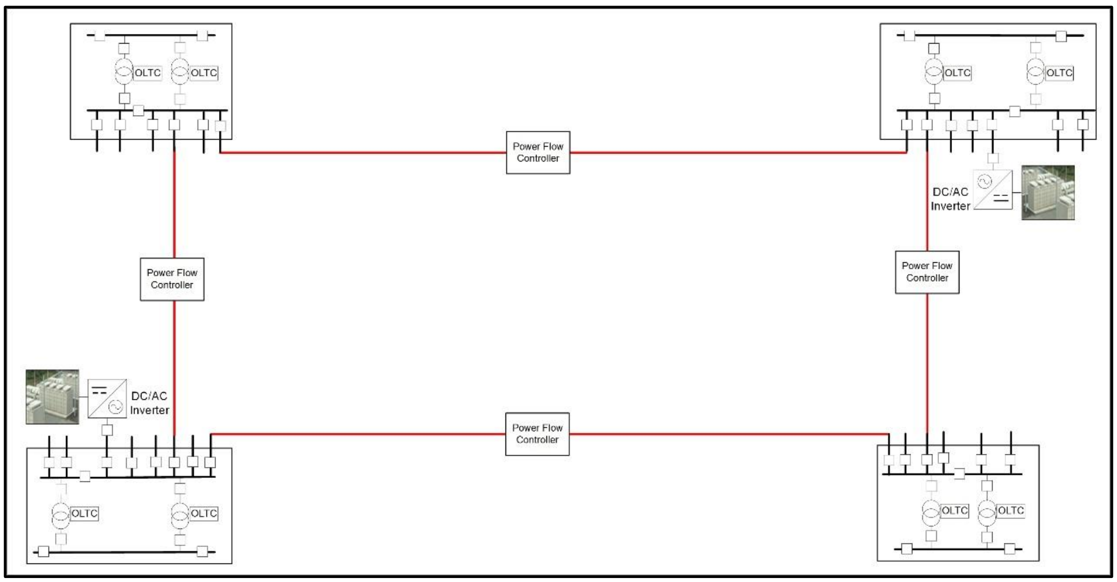

Figure 14 Substation Storage Sharing Ring Structure

Use of networks of distribution-connected storage elements requires a control structure and consequent communications structure that supports real time operations, as well as industry structure that can effectively use the DSN. In line with Specification 1, the DO should own and operate the storage units in the substations, and the DSO function/role should be responsible for directing the operation of the storage units when they are being invoked for BES level resilience purposes. The coordination at the T/D interface between the TO and the DSO still holds and should not be overridden. For distribution level resilience functions, either DSO level control or distributed autonomous control may apply. The communication structure of Specification 4 supports both centralized and distributed operation of the DSNs.

Figure 15 shows control modes and resultant control structures for DSNs. Control paths are marked in red. There are three modes:

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[28] This is a form of grid energy storage in which energy flows in and out of storage from and to the electric grid at comparable high rates.

- Local autonomous mode – each storage unit has a local controller that operates independently of the others, using only local measurements. This places no requirement on operational communications although the storage controllers may be subject to supervisory communications.
- Distributed mode – each storage unit’s controller can communicate and cooperate with the others. This places a peer-to-peer communications requirement on the communications network.
- Layered mode with DSO – this mode enables the TSO to make use of the DSNs for resilience purposes by interacting with the DSOs, which then exert direct control on the storage units in their service areas.

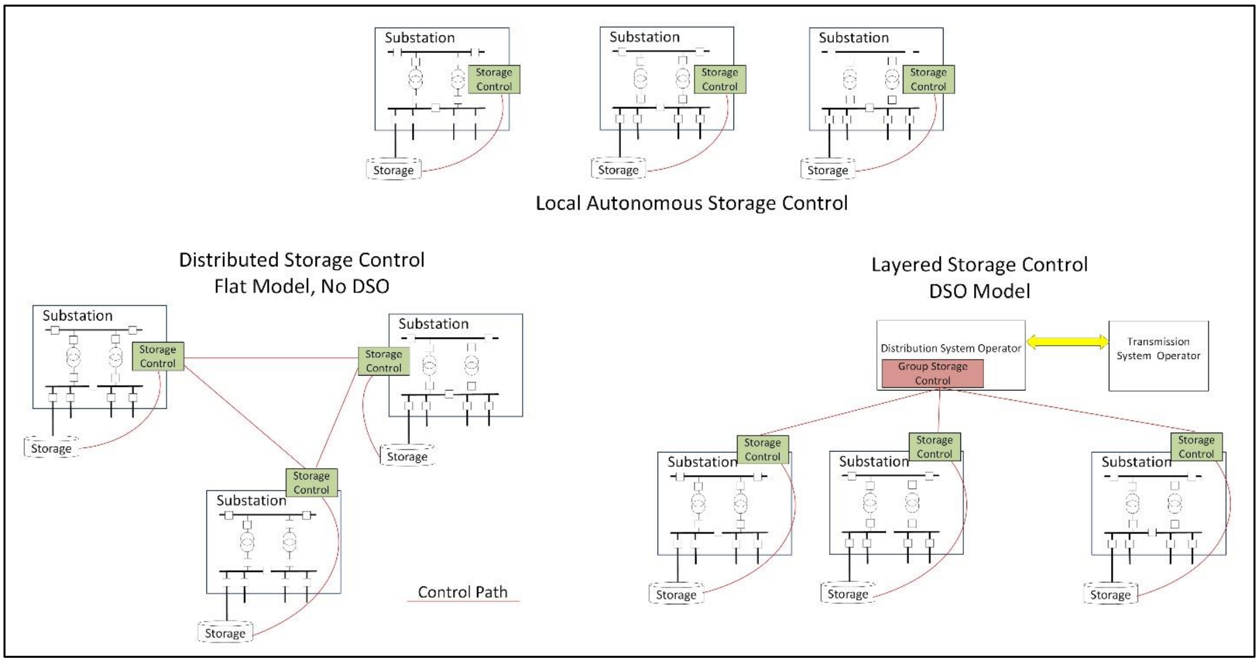

Figure 15 Distribution Storage Network Control Structures

The layered mode is consistent with both the DSO model of Specification 1 and the Laminar Coordination Framework structures (see below).

Specification 5 details:

5.1 Use fast bilateral bulk storage in distribution substations (or otherwise connected to primary distribution feeders) as core infrastructure elements.

5.2 Where it is not feasible to locate storage in a substation or comparable location, share storage in one or more substations with one or more other non-storage distribution substations.

5.3 Use primary distribution feeder connections and power flow control to interconnect substations for storage sharing.

5.4 Provide for autonomous local control, distributed cooperative control, and hierarchical control modes to support multiple methods of operation of the storage units.

5.5 Do not bypass the distribution operator to use DSNs for BES purposes. Work through the DSO/TO interface in all cases.

Specification 6: Laminar Coordination Networks

A distributed system in one in which the various decentralized elements cooperate to solve a common problem, such as grid operation. The mechanism by which this cooperation occurs is *coordination*. Laminar Coordination Framework is a generator for coordination architectures for electric power systems that is derived from the mathematics of utility maximization via layered decomposition.[29] The resultant structures are called Laminar Coordination Networks. Figure 16 illustrates the basic structural elements that are used to compose Laminar Networks. These derive from a mathematical approach to solving a wide class of optimization problems with multiple coupled constraints. The mathematics induce a structure that has been generalized to generate coordination architectures. The elements in the figure provide building blocks and structure to assemble Laminar Networks for any specific grid or portion of a grid. Note that each Laminar node requires intelligence (computing capacity). While this could be virtualized, placing intelligence at the nodes allows for resilient operation when a Laminar Network fragments (separates) due to communication link or other failure mode issues (Core Resilience Architecture principle 12 and the ULS normal failures principle).

The Laminar Coordination Framework also anticipates the issue of third party owner/operators of DER that is participating in grid operations. Third parties can provide the completion of Laminar Networks and handle communications to the non-utility DER devices.

[29] 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 .

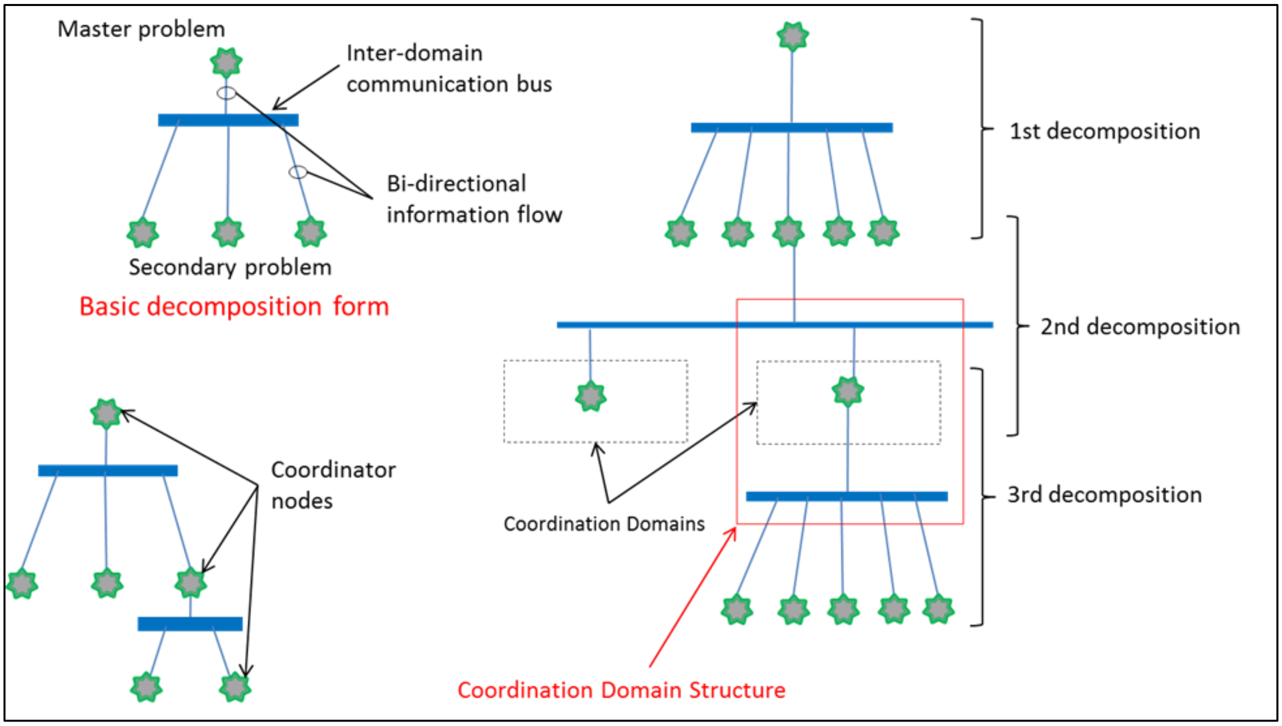

Figure 16 Laminar Coordination Framework Structural Elements

Figure 17 shows an example of a Laminar Network. Note that the DSO/TSO structure of Specification 1 is completely compatible with the Laminar Coordination Framework. In fact, the coordination root node could be extended to the TSO but typically does not have to be, due to the definitions of the roles and responsibilities for the total DSO model, which were derived in part from Laminar Coordination Framework considerations.

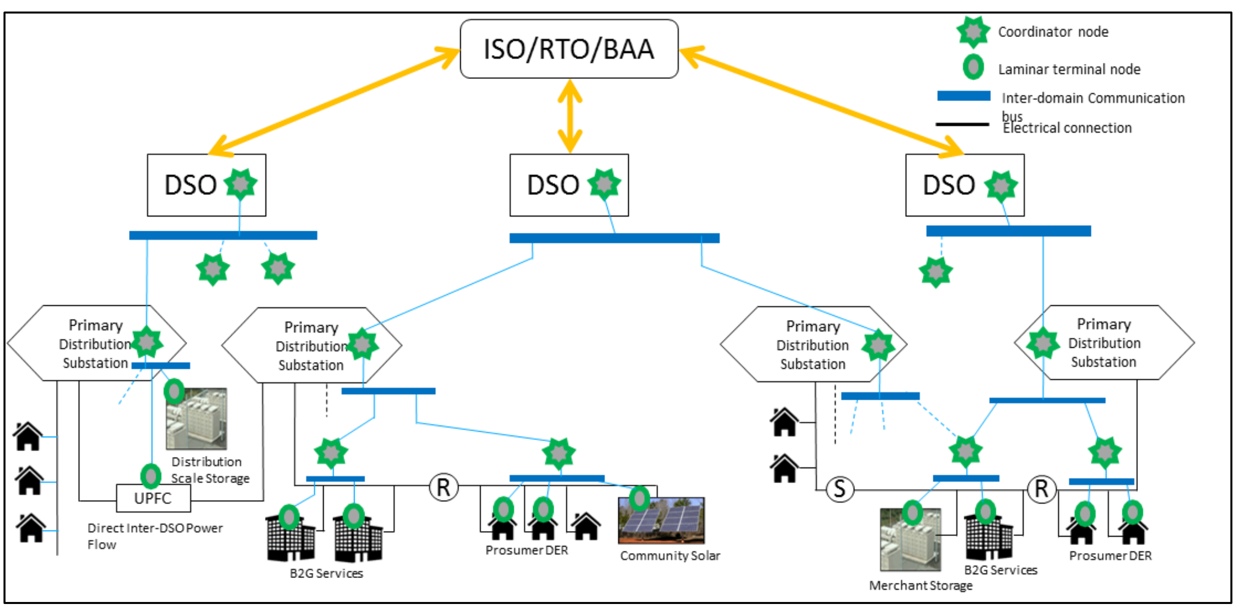

Figure 17 Example Laminar Network

Specification 6 details:

6.1 Use the Laminar Coordination Framework to develop specific Laminar Networks that correspond to the actual physical system being coordinated.

6.2 Follow the Framework to define logical information flows for the coordination process.

6.3 Maintain Laminar structure, even when DER are being coordinated via aggregators or other third parties.

6.4 Third parties can host Laminar nodes on behalf of the DER they aggregate.

6.5 Connect aggregators to the appropriate DSO to participate in the coordination data flows for the DER they manage in the service area of the DSO. Aggregators and other third parties may connect to more than one DSO if they have DER in more than one DSO service area (refer back to Specification 1).

6.6 Provide computing capacity at the node locations to implement Laminar node functions.

Specification 7: Logical Energy Networks and Distribution Virtualization

DER may be used to support grid resilience but the present structure makes this difficult. Figures 4 and 5 above show that distribution systems are organized substation service area. This is done in part by physical infrastructure but more importantly by imposition of virtual structure via control systems. The existing structure represent a constraint on the use of DER for resilience purposes at both the distribution and BES levels. Logical Energy Networks are structures for the virtualization of distribution systems to access the latent capacity of DER for resilience purposes. A Logical Energy Network (LEN) is a distribution level virtual structure specified and enforced through coordination and control processes. It is a portion of a distribution system that is segmented in a way that is roughly analogous to bulk system Balancing Areas. It is not a virtual power plant. There may or may not be underlying circuit elements (sectionalizers, boundary sensors/meters, power flow controllers) involved. LENs may be thought of as virtual microgrids but islanding capability is not required.

A LEN is a segment of a primary feeder with associated devices and loads. Ideally, each LEN has three energy sources available to it:

- Fed from two primary distribution feeders
- Some amount of DG/DS resource internal to the LEN that is utility controlled or coordinated
- Other non-utility-controlled DER may or may not exist

A LEN has logic that manages:

- Local balance (see three sources)
- V/VAR regulation (local)
- Grid services resource mgmt. (local)

LENs operate in a cellular fashion, like a microgrid network and can function as “resilience cells.” LENs operate autonomously when needed and are globally coordinated normally via Laminar Coordination networks. LENS are disjoint, meaning they do not overlap in terms of physical infrastructure. Lens are contiguous and complete, meaning they cover the entire distribution system with no gaps. Figure 18 shows a distribution feeder with LEN virtual structure superimposed.

This structure recognizes two classes of DER:

- Edge resources (non-utility owned/coordinated by DSO)
- Core resources (utility owned/controlled by DSO)

LENs interact with each other (on a neighbor basis) to carry out:

- power wheeling
- interchange
- intra and inter-LEN outage support
- inter-LEN V/VAR support

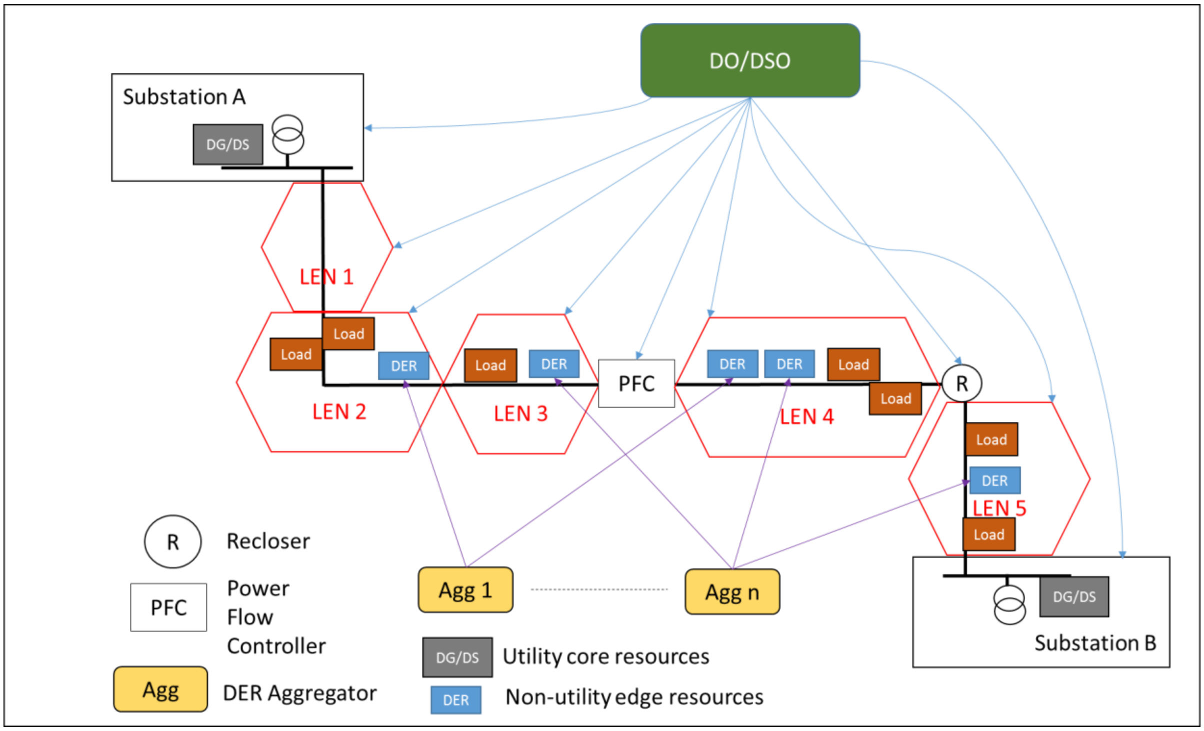

Figure 18 Example Feeder LEN Structure

Given the LEN structure, Figure 19 shows the new stack model for the grid. Note the degree of parallelism between the structures of the BES and the LEN-based distribution system. In order for the BES to make use of the LENs, it must operate through the DSO, as indicated in Specification 1.

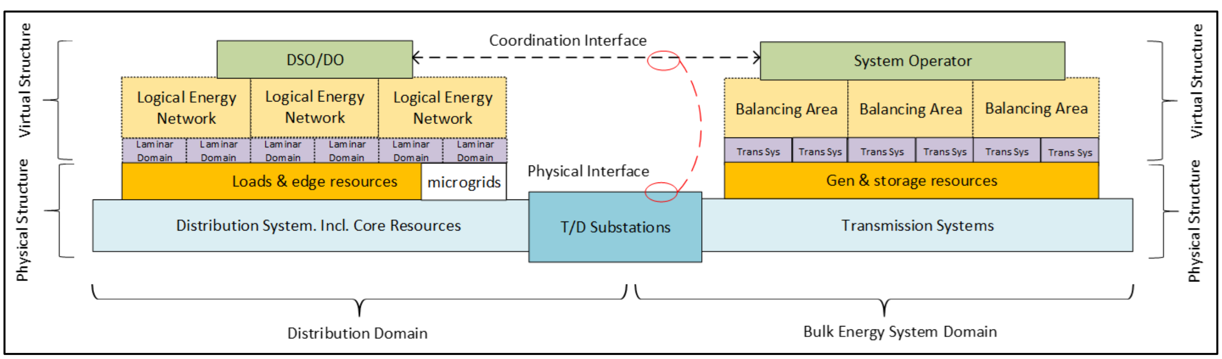

Figure 19 Grid Stack Model Diagram with LENs

Note the LENS are comprised of Laminar Domains; in fact each LEN comprises a Laminar Domain itself, but may be further decomposed layer wise. Organizing the DER under the LEN/Laminar structure improves the effectiveness with which the DSO makes use of the DER on a spatially and temporally granular basis for both itself and the BES. For more information the concept of operation for LENs, see white paper *Logical Energy Network Concept of Operations*.

Note that LENs are compatible with Laminar Coordination. Each LEN can function as a Laminar Coordination domain and the Laminar node can coincide with and be hosted on the same computing element as the LEN logic. Both are compatible with the distributed intelligence approach of the Open Field Message Bus.[30,31]

Other distribution level structures are also potentially useful for grid resilience purposes, such as agile/fractal grids and microgrids. These are considered in detail in other GMLC reference architecture tracks.

Specification 7 details:

7.1 Each distribution system is comprised of a set of non-overlapping, contiguous Logical Energy Networks.

7.2 Each LEN comprises a Laminar Domain and may be further decomposed into lower level Laminar Domains as needed.

7.3 Each LEN has two separate feeder connections plus an internal utility-controlled set of core DER (DG and/or DS) resources so that it has three ways to obtain energy.

7.4 Each LEN has a local control/intelligence capability that supports local load and energy resource management.

7.5 LENS are coordination via Laminar Coordination and a DSO.

7.6 LENs may or may not have physical islanding capability but can act as virtual microgrids when necessary.

7.7 LENs act as combined load and energy resources for the DSO.

7.8 LENs supports neighbor LENs via power wheeling and interchange, outage support, and Volt/VAr support.

Specification 8: LEN Source Decoupling Circuit Structure

Each LEN is a subsystem that has been virtualized and has an underlying physical subsystem. The LEN definition provides for support from two grid primary feeder paths. There are several ways to accomplish this and they are not all equally resilient. Applying principles 5, 7, and 8 leads to the concept of progressive structural decoupling. Figure 20 shows a progression from left to right in which the grid connections to the LEN are increasingly more resilient, due to increasingly wider path separation and

[30] OpenFMB Collaboration site: https://openfmb.github.io/

[31] S Laval and B Godwin, Distributed Intelligence Platform (DIP) Reference Architecture Volume 1: Vision Overview, January 5, 2015.

source redundancy. From left to right, the arrangement progresses from two feeders on the same substation bus to two feeders on separate buses in the same substation to two feeders from two separate substations on the same transmission system, to finally, two substations connected to two separate transmission systems.

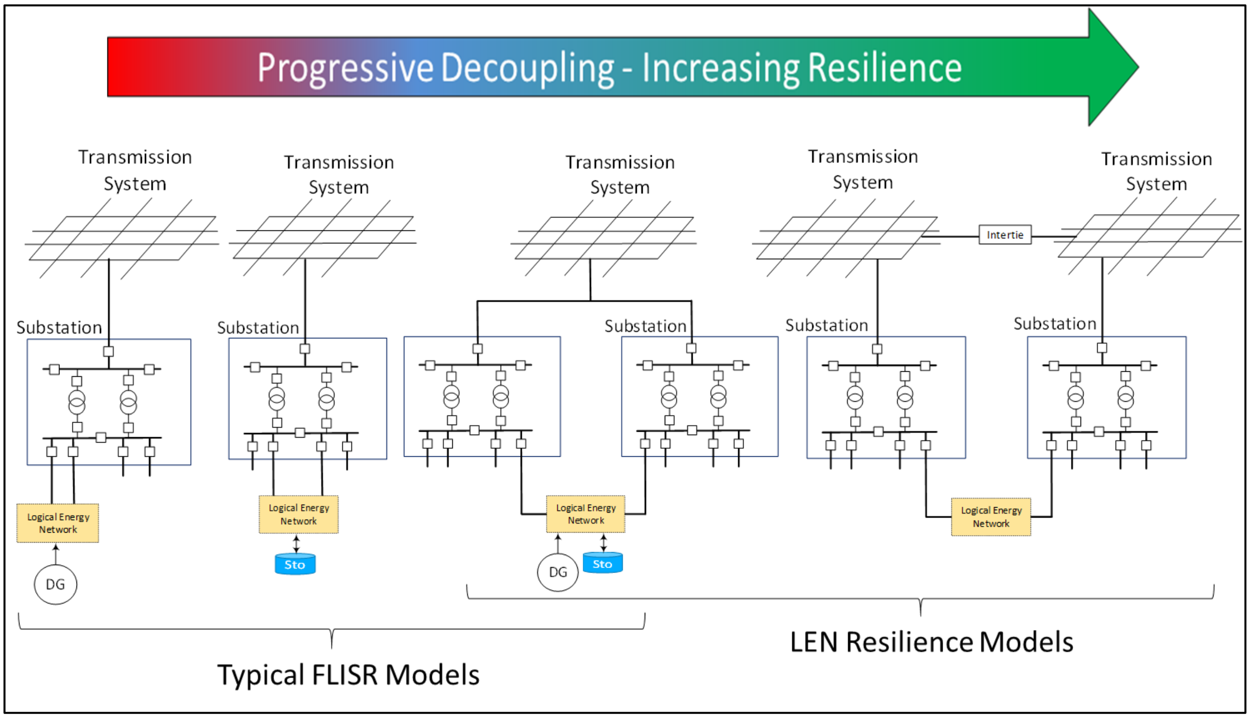

Figure 20 LEN Feeder Circuit Resilience Structures

Clearly it is not always possible to choose the electrical interconnection structure, especially in the last case of two transmission systems. Understanding this concept provides the means to evaluate this aspect of resilience and to choose the level of resilience in this structure when practical options are available. Note that the LEN two feeder requirement implies partial meshing of distribution primary feeder circuits. This is consistent with use of FLISR.

Specification 8 details:

8.1 Supply any given LEN from at least two distinct distribution primary feeders.

8.2 Arrange the two feeders to be supplied from two different substation buses, where feasible.

8.3 Arrange for the two buses to be contained in two separate substations, where feasible.

8.4 Arrange for the two substations to be supplied from two different transmission systems, where feasible.

Specification 9: Distributed Intelligence Platform

Distributed coordination and control require both computing and communications support. For the computing portion, digital processing capability must be located throughout the grid. At each level in the grid hierarchy, connected processing capability must provide not only bare metal computing hardware but three layers of firmware/software. Figure 21 illustrates the places in the grid where computing can be located and examples of the contents of the three soft layers that reside on the computing hardware. The combination of these and the communications layer constitute a distributed intelligence platform.

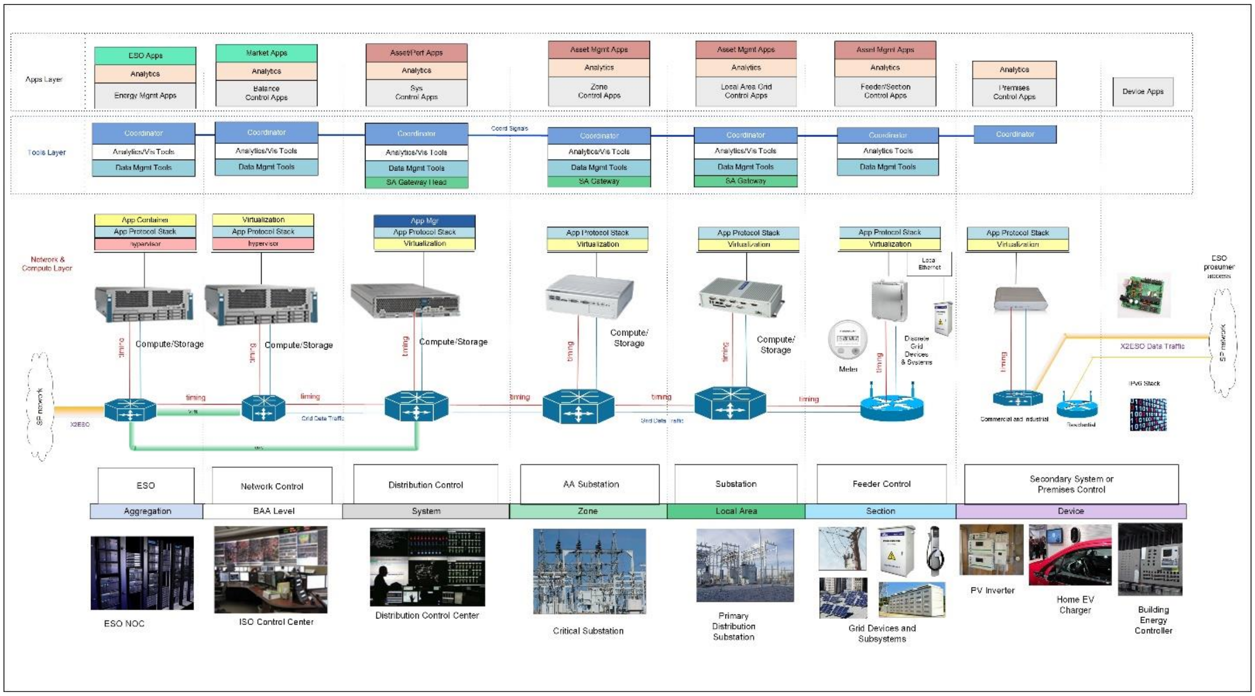

Figure 21 Electric Grid Distributed Intelligence Platform

Note that the use of Laminar Networks (Specification 6) implies that computing and communications must extend past the boundaries of the utility itself and into the DER devices and third parties that participate in grid operations. In addition to the control or operations centers, intelligence may exist in the substations, at the distribution feeder sensing and control devices, at the residential and C&I meters,[32] in solar PV and battery storage inverters, in electric vehicle chargers, and in responsive load devices. Computing capacity for distributed intelligence may even reside on the communications devices themselves.

[32] B Seal, Transforming Smart Grid Devices into Open Application Platforms, EPRI report 3002002859, July 2014. Available online: http://smartgrid.epri.com/doc/SG%20Informational%20Webcast%20Open%20Apps%20V2.pdf

Specification 9 details:

9.1 Provide computing hardware and software support for applications as needed throughout the grid.

9.2 Use a five layer platform model: communications, computing hardware, operating firmware/software, tools software, and applications software.

9.2 Provide the means to manage applications for the distributed computing platform, including FCAPS, over the air download and update, and application control.

9.3 Provide communication connectivity that supports both device-to-control center communication and peer-to-peer communications, including Laminar Network coordination communications.

9.4 Include intelligent grid devices such as advanced switches, inverters, and sensors in the distributed intelligence architecture, even if they cannot host third party applications.

9.5 Incorporate comprehensive cyber security measures in the communications networks and the computing devices. Include six-wall physical security for grid (electric utility-owned) devices.

Specification 10: Communications Structures

Communications networks are key components since the electric infrastructure is decentralized. For distributed operations, simple hub-and-spoke networks are insufficient unless XMPP-style relay communications are acceptable, but that approach poses a single-point-of-failure issue. Generally, electric utility networks require path redundancy and many must provide low latency as well. While some literature suggests that electric utility networks may be divided into only three tiers (WAN, FAN, NAN), in fact for electric grids to be resilient, we must consider at least two more tiers and also be concerned with network-based timing distribution.

10.1 Wide Area Network (WAN) structure for private networks is a multi-aggregation ring topology with linear aggregation strings. Figure 22 illustrates the basic form. This structure can be scales as needed and can be implemented in a proportionally manner, so that incremental build-out is possible.

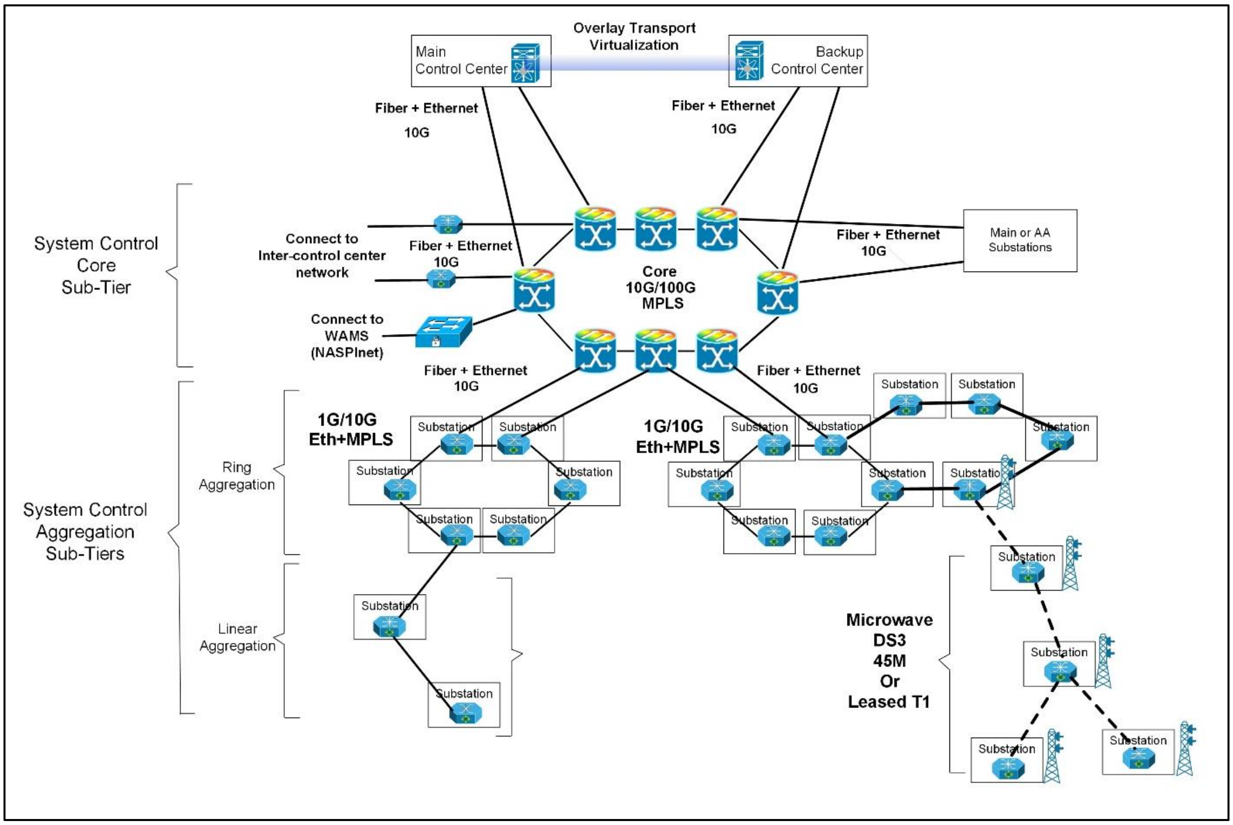

Figure 22 WAN Structure Diagram

10.1 Specification details:

10.1.1 The topology consists of three tiers. The top tier is a ring with very high data rate capacity.

10.1.2 The second tier consists of multiple (as needed) aggregation rings with high data rate capacity. These rings may or may not be interconnected with neighbor aggregation rings. The multi-ring structure may be scaled up or down as needed.

10.2.3 The third tier consists of linear aggregation strings as needed, typically to reach remote locations.

10.1.4 Control centers and critical substations use dual redundant connections to the top tier ring.

10.1.5 Multiple physical media may be employed as needed for engineering reasons.

10.2 Substation networks for critical infrastructure in a high resilience architecture use the redundant tree topology of Figure 23. A variety of network topologies are available for substations and less critical substations may use less resilient approaches.[33] 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).[34] The cited document also provides topology comparisons and comparison of IEC 61850 over Ethernet vs. IEC 61805 over UDP/TCP over IPv4/v6.

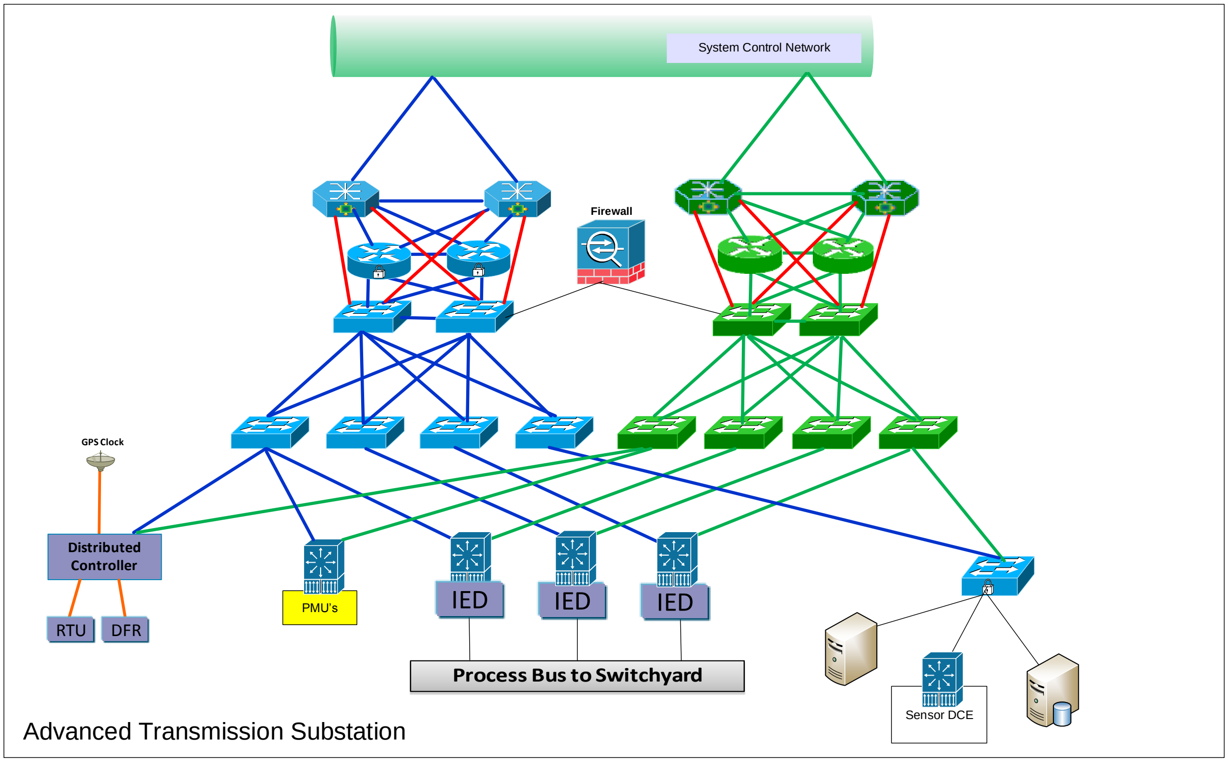

Figure 23 High Resilience Substation Communication Network

[33] 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.
[34] N. Yadav and E. Kapadia, Substation of the Future: Improve Network Reliability and Protocol Interaction, Grid Interop, December 2010.

10.2 Specification details:

10.2.1 Use meshed two-tier dual tree network topology.

10.2.2 Provide dual connections to the WAN(s).

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

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

10.2.5 Use full meshing for the upper tier of each tree <see Visio *file GMLC 1.2.1 Network Topologies v0.1, Full Mesh tab* >

10.3 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 24 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.

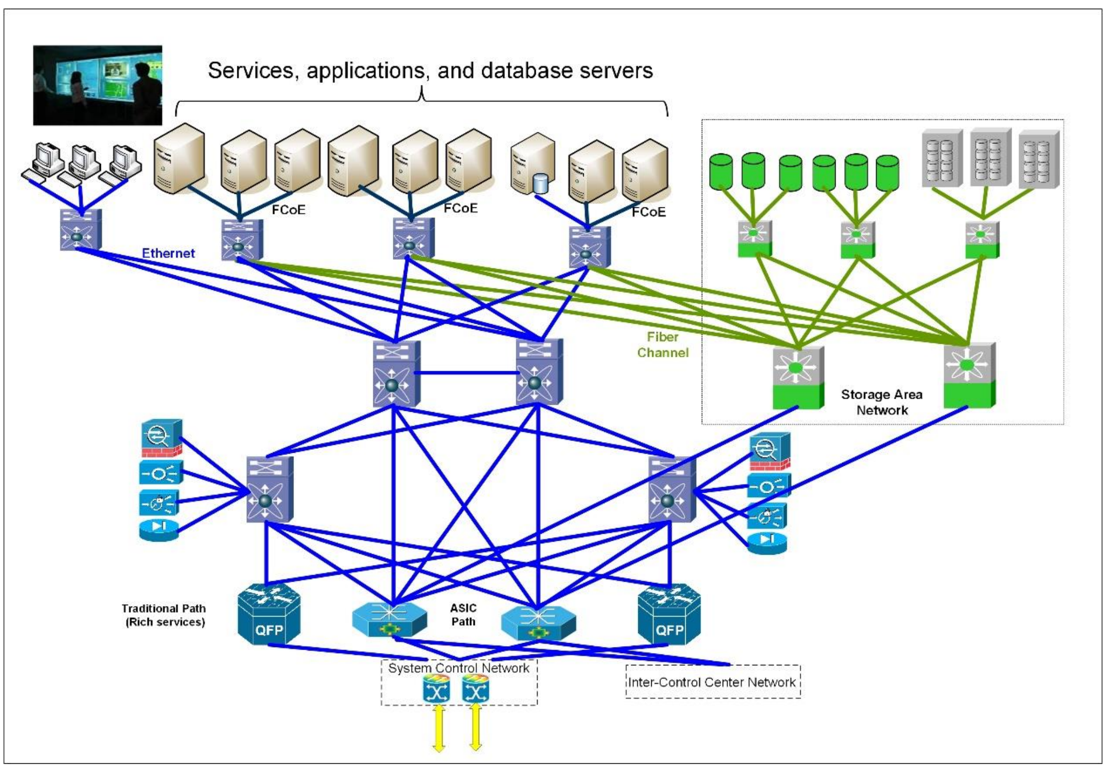

Figure 24 High Resilience Control Center Communications Network

When telecommunications service providers are used for wide area communications, the dual service provider model with redundant paths as shown in Figure 25 avoids the single point of failure problem (in this case outage of a service provider). Note the dual redundant connections on each end.

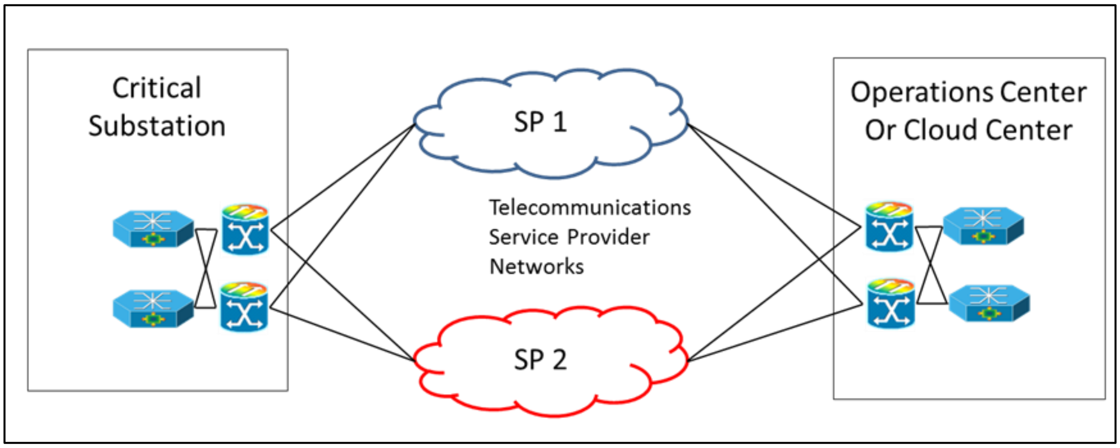

Figure 25 Redundant Telecommunications Service Provider Communications Structure

10.3 Specification details:

10.3.1 Use mesh multi-path topology.

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

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

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

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

10.4 Timing Distribution Redundancy

Synchrophasors 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.[35] Consequently, additional sources and methods of synchronization are desirable in line with the NASPInet 2.0 architecture principles.[36] In Figure 35, 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.

Phasor Measurement Units (PMUs) and other elements of grid measurement and control require timing distribution or another mean of establishing synchronism (agreement among the elements on the present time or time stamp value). The typical solution for this has been to use 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. Consequently, additional sources and methods of synchronization are desirable in line with the NASPInet 2.0 architecture principles.[37] In Figure 26, 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 PMU communication network.

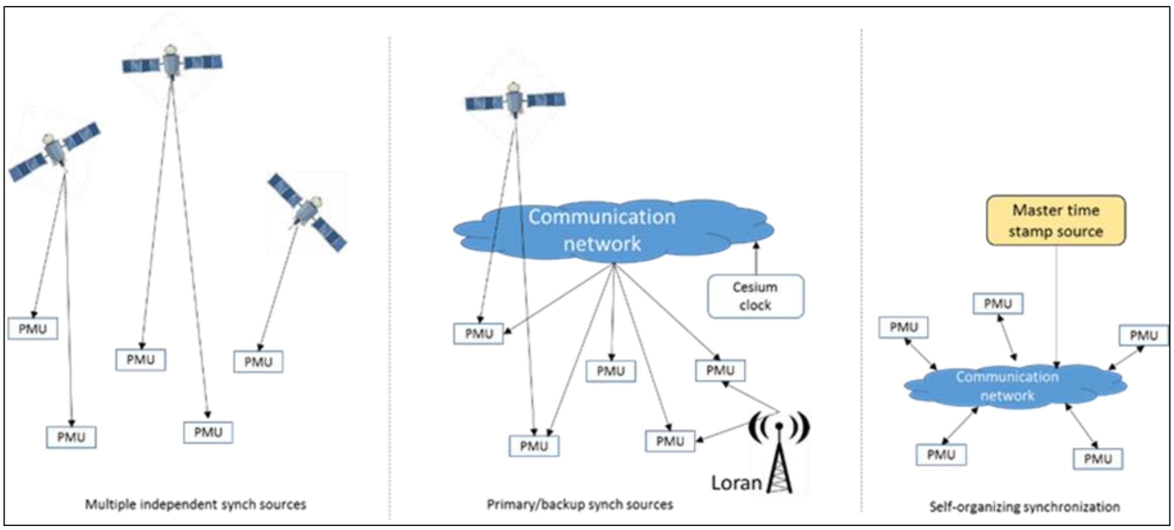

Figure 26 Network Timing Sources

Alternatively, a sensor network such as a PMU network may be self-synchronizing[38] 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

[35] 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
[36] 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
[37] NASPInet 2.0 Architecture Guidance, pending release by NASPI.
[38] 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.

able to communicate with each other, including across organization boundaries in the case of transmission-level PMU networks.

Figure 27 illustrates a multi-organization network architecture for timing distribution.

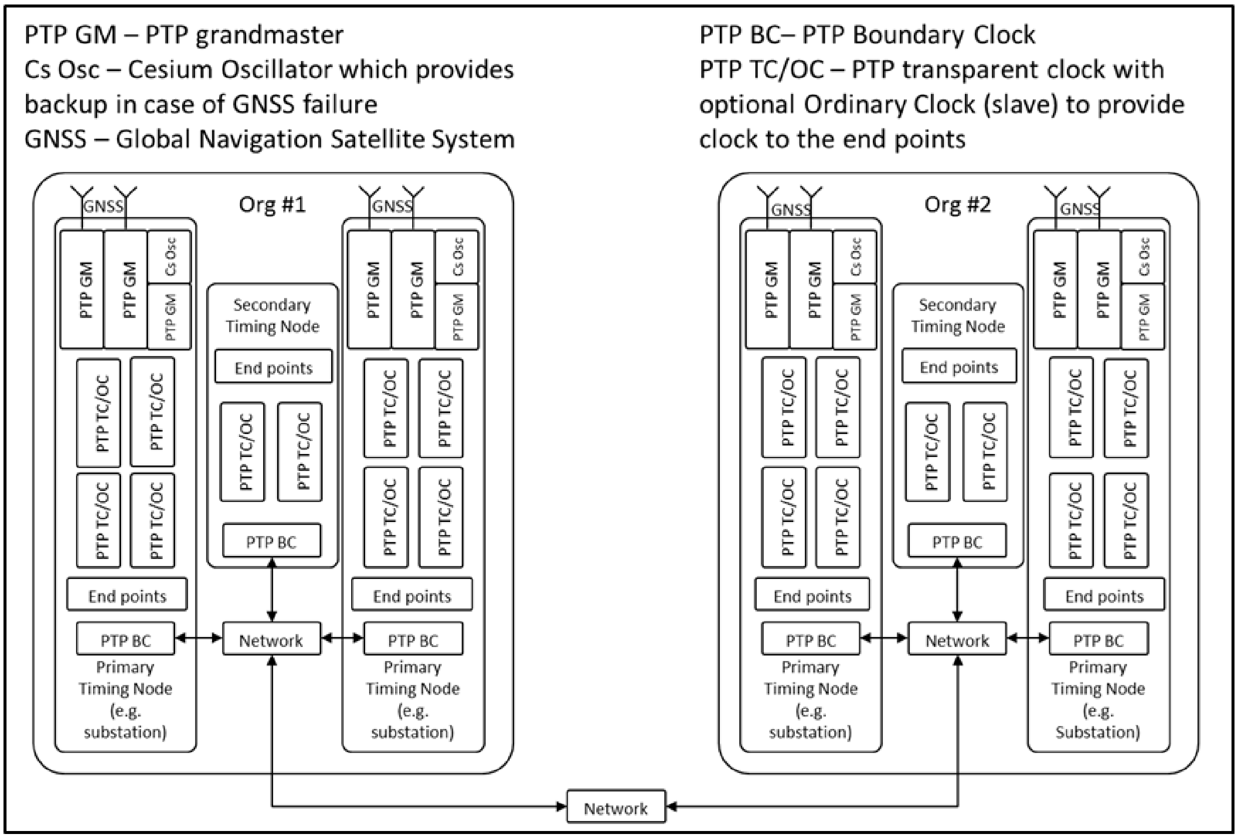

Figure 27 Wide Area Timing Distribution Architecture

Specification 10.4 details:

10.4.1 Provide time distribution at every hop in the network.

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

10.4.2.1 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

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

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

10.4.4 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.

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

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

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

10.4.5.3 Receiving BC distributes time further in own organization.

10.4.6 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 us is required between different systems then accuracy can be kept by the atomic clock for 27.77 hours, assuming initial time offset of 0.

10.5 Wind Farm Monitoring and Control Communications

Unlike traditional power plants, wind farms consist of many generators (wind turbines) which are spatially dispersed, and may even be offshore. Communications with the turbine towers is generally via optical fiber. Since the turbines may be spread out over many square miles, it is not feasible to use dual tree communication network topology but path redundancy is still necessary for resilience. A combination of multi-ring and multi-connection structure can provide redundancy in a practical manner. Figure 28 shows the basic schema.

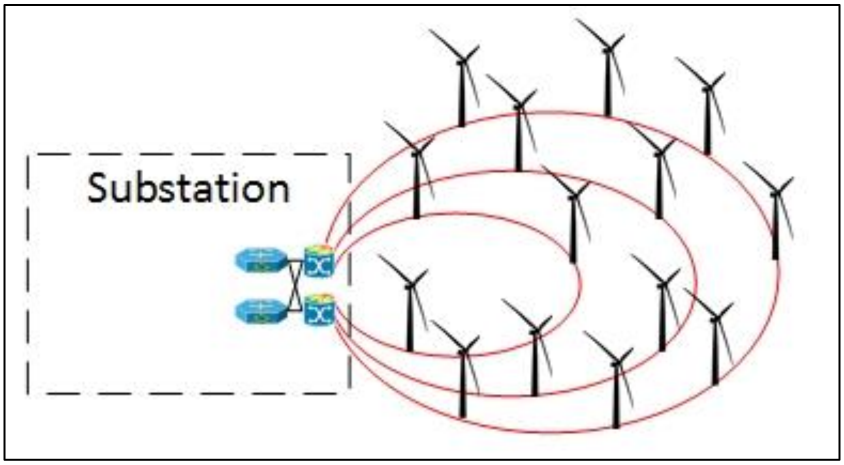

Figure 28 Wind Farm Communications Structure

Each ring provides two paths to reach any given turbine, so breaking a fiber in a single location does not result in loss of communications. Using multiple rings keeps the number of turbines per ring manageable and segregates the turbines into subsets that operate independently from a communications standpoint so that complete failure of a ring does not have to compromise all of the turbines.

Note that a similar structure can be used for solar farms.

Specification 10.5 details:

10.5.1 Divide the turbines into groups and connect each group with a separate optical fiber loop.

10.5.2 Connect each fiber loop to two separate switches at the substation.

10.5.3 Use redundant mesh connections between the switches and the routers in the substation.

Specification 11: 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 entity-relationship diagrams that describe the as-is and to-be grids and the specification of grid components emphasizing high-resilience operations. While this document specifies the key data flows and data architecture guidelines applicable to high-resilience, 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.)

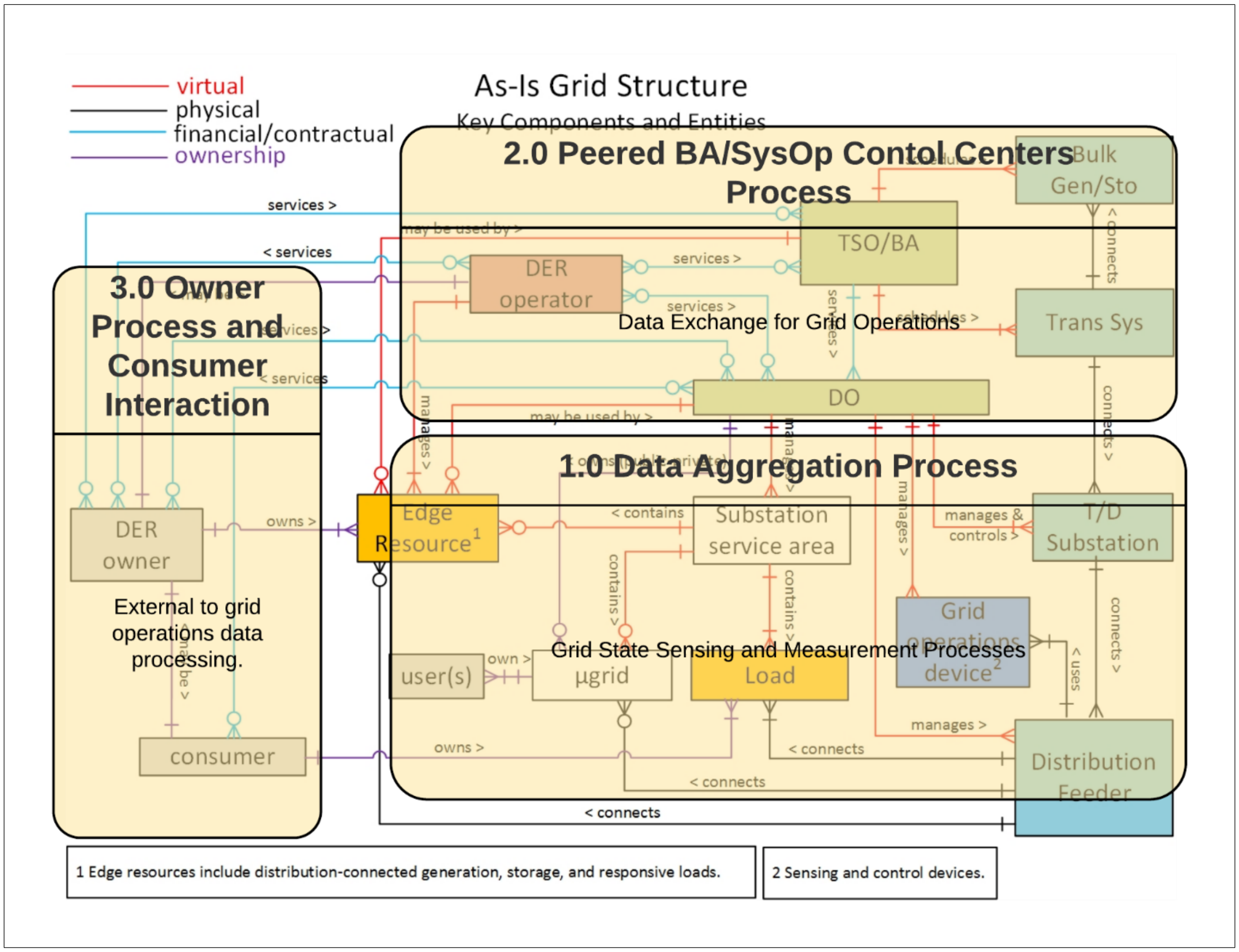

Figure 29 Data Processes Overlaid on As-Is Grid Entities

We use the ER description of the primary constituents of the grid as-is to outline the new high-resilience oriented data architecture constructs we specify in this section. Figure 29 is an overlay of the primary data components on the as-is grid structure (illustrated earlier Figure 4). We divide the main data components into source data that is collected and aggregated, which is then transferred to the operations and control center process data, and finally the user and applications-facing data processes. The source sensor data is represented in the "*1.0 Data Aggregation Process"* module representing (typically minimal state) aggregated information from distributed energy and edge resources including microgrids and loads. The operations and control centers data process is shown in the *2.0 Peered BA/Sys OP-Control Centers Process* module which holds and manages the data for system state and control. This process includes data exchange with peers, storage of monitoring information in historians, and providing typically open-loop directives used in grid control processes such as Automatic Generation Control. Finally, the system data from aggregators and operations centers may be exchanged with owners and consumer entities denoted by *3.0 Operator Process and Customer Interaction* that request services and enable data exchange for purposes that include, in full generality, demand-response, trading, and interactions with edge services operators. Recall that this data flow architecture in present-day (as-is) grids only supports open-loop and delayed response operations which is an anti-resiliency pattern.

The operation of a resilient modern power grid requires multiple closed-loop feedback controls that increasingly rely on sensor measurement data that is dynamic, reliable, tolerant to partial and intermittent connectivity, and secure. We discuss below the data architecture components that derive from the requirements of the high-resilience architecture specifications described earlier.

Specification 1 and 2: Total DSO/TSO Industry structure and Transmission Observability Platform requires that DSO must have much higher visibility than existing systems into their operational data, control constructs, and must be the energy data interface to TSO and peers. Transmission Observability Platform requires a common addressable interface to data holdings across SO/RC, Utilities, and Edge Resources.

Specification 3: Backup Protection and Redundancy requires that data flows are replicated, and services have spatial and functional redundancy. Traditional database redundancy technology is an established and available approach. Functional redundancy will be achieved by estimating state and using peer information to obtain fuller information on system state in case of system stress and strain.

Specification 4 and 5: Distribution Layer Structure and Observability and Distribution Storage Networks requires a move away from siloed structures by proposing that layers provide both redundancy (through peer to peer information exchange within a layer), and self-sufficiency with sufficient information coverage within a single platform that encapsulates one or more layers and components to enable independent operations. The design of the data flows here requires the architecture to operate with internal consistency, but also to present a uniform set of abstractions to peers. A thematic way of describing this is through micro-services that are assembled into a single function and disassembled when operating as a distributed system. Note that this data architecture is intrinsically not the easiest to implement – it's far easier to centralize state and operate in an all or nothing manner. Supporting distributed resiliency has inherent system design complexities. The "CAP theorem" [Ref: Brewer2005] allows you to have only two of Consistency, Availability, and Partition tolerance for information state in a distributed system. This result indicates that when operating a resilient system, the data available at times cannot be assumed to be current unless other supporting heartbeat or similar time synchronization information is available. Thus, data carrying time distribution and synchronization are required. (Also note the specification section in this document on timing distribution.) The resilient grid must continue to operate its physical power balance and stay within grid device operational limits in partial connected state as well as a fully connected state. This inherent redundancy can lead to replicated computations as well as inefficient power delivery in the interest of resilience and flexibility.

Specification 6: Laminar Coordination Networks rely deeply on distributed data flows that exchange periodic information that support eventual consistency. For a resilient grid architecture, the state space of distributed control is accomplished by supporting multiple operational instantiations between fully disconnected to connected operations. (This is necessarily discrete states because the physical networks and entities do not exist in "continuous" space.) For pre-defined disconnected and partially (to full) connected operations, peering data flows must communicate system state and operational heartbeat information. These require logical processes that are independent of the physical location of the infrastructure. Data flow services should make no assumption of the spatial location or context of any particular service.

Specification 7 and 8: Logical Energy Networks and Distribution Virtualization is a laminar decomposition realization for grid stress and strain contingency support and resilient operations. Enabled by distribution virtualization, typical LEN need to include energy sources fed by two primary distribution feeders, certain amount of DG/DS resources. The data flows must support local balance and grid services resource management (including V/VAR) regulation. (This operation is outlined in the LEN Concept of Operations document.) As in previous data architecture configurations, peered data exchange is a critical structural construct to enable the LENs from a data systems point of view.

Specification 9 and 10: Distributed Intelligence Platform and Communications Structures requires a layered platform model to store and process data from the device hardware and sensors, firmware, operating systems, and communications systems to application devices.

We address the data flows that the above architecture specification with the resiliency enabling data flow diagram in Figure 30:

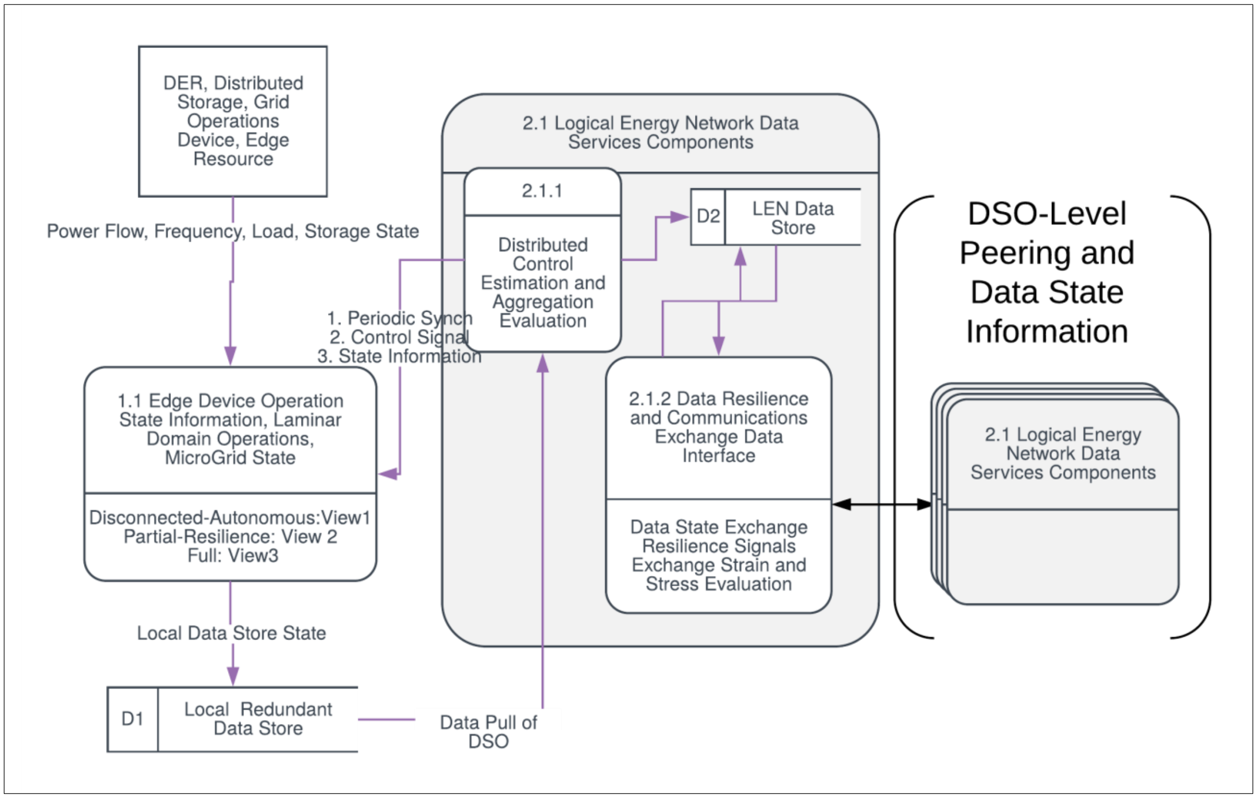

Figure 30 Data Flows for High-Resilience Grid

We note the key changes from the as-is data flows as follows. The previously shown high-level “Data Aggregation Process” module is now shown in greater detail in the left of Figure 30. Data is stored locally to enable the laminar domain operations. Support for disconnected and autonomous operations, and partial and full resilience operations is explicitly implemented. This requires computing and data middleware at the edge of the grid with built in redundancy for data communication failures and explicit operation modes with only partial state. The operations and control centers data module “Peered BA/Sys OP-Control Centers Process” is refined to become the “Logical Energy Network Data Services Components” module. This modernized data process synchronizes state periodically with the edge device control laminar domains and sends feedback control signals that are derived from the state data. This module also operates a Logical Energy Network distributed data exchange function that includes aggregation and data exchange with peers, and storage of monitoring information in historians. The support of communication messages and signals that exchange stress and strain information are fundamental to the degree of autonomy and peering the edge devices are given and when they are incorporated back into broader DSO and TSO operations.

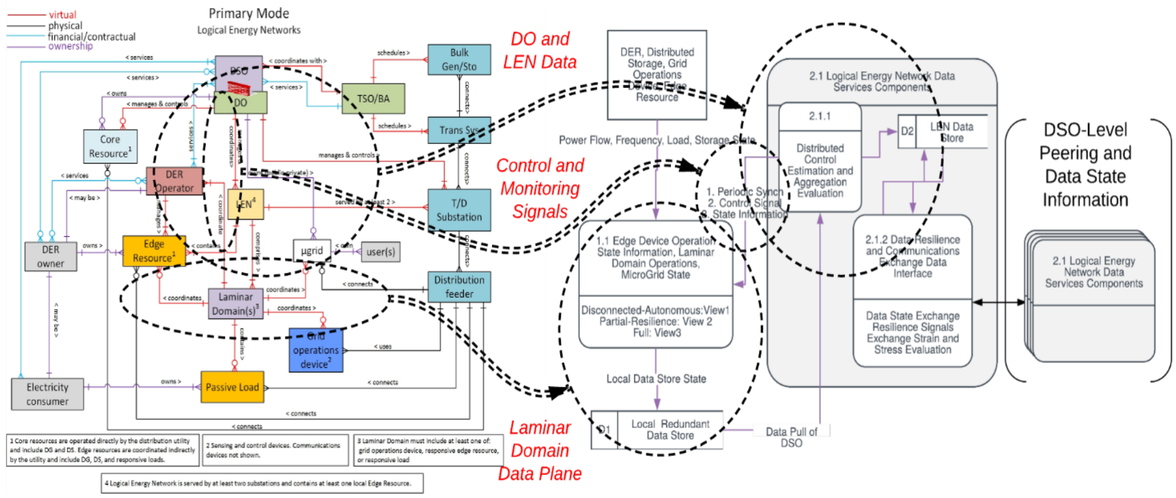

Figure 31 New data flows to support Laminar Domains and LENS

Figure 31 illustrates the new data flows that are required by the architectural recommendations in the new high-resiliency architecture. The new architecture components are presented and discussed below in Figure 32. We illustrate three key mappings: (i) data flow and processes that are associated with the laminar domain components that coordinate the edge resources, (ii) the LEN configuration that is central to coordinating reliability in the distribution systems, and (iii) the new control feedback data that enables the coordination algorithms that provide resiliency in the grid.

The key resilient data architecture specifications emerge from the requirements that drive the data presence near the edge of the network, addressable interfaces for Total DSO/TSO Industry structure and Transmission Observability, Distribution Layer Structure and Observability through Laminar and Distributed Coordination, LEN structures that peer data exchange, and ultimately enhanced distributed intelligence and communication:

Specification 11 details:

11.1 Edge devices, microgrids, DERs must retain data within an accepted resilience time window.
11.2 The locus of laminar coordination must store the data using established resiliency and redundancy measures.
11.3 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 Utility, DSO, and LEN levels. (This must be implemented similar to DNS lookup and addressable IP ports.)
11.4 The data flows must support the same interface for flexible configuration of laminar domains within the domain and for external requests. (This is similar to service APIs that are made available and extensible through systematic namespace management.)
11.5 A Data flow service for eventual consistency must be implemented.
11.6 Data service must be available on stress and strain events and return valid (even if valid across all local data at a prior timestamp) data. Control protocols must operate with partial data resident at a LEN.
11.7 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.

Composite Structure Views

The use of DER as resilience asset leads to a grid structure in which distribution systems are virtualized into Logical Energy Networks coordinated via Laminar Networks and managed using the total Distribution System Operator role set to interface with Transmission System Operators. This approach requires distributed intelligence at the distribution grid level, and benefits from silo-to-layer conversion of sensing, communications, and control into a platform model where sensing and communications become an infrastructure layer supporting many decoupled applications. This layer model applies at both the transmission and distribution levels and not only enables other architectural resilience structures, but in itself adds structural resilience.

Grid E-R structure with DSO and LENs

Figure 32 shows the revised grid E-R model for a DSO/LEN structured grid (compare to Figure 4).

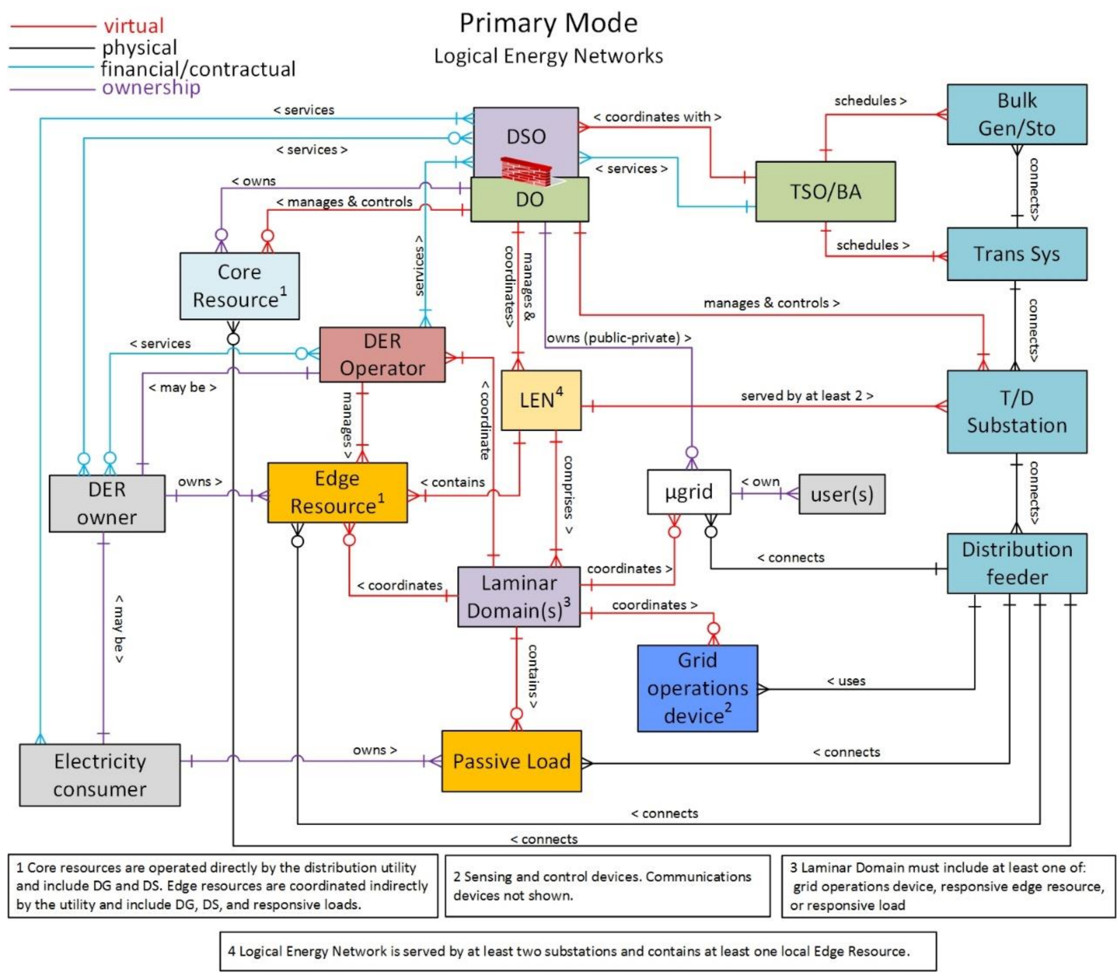

Figure 32 New LEN/Laminar/DSO-Based Grid Structure E-R Diagram

Note that distribution systems are decomposed into LENs and Laminar domains and that distribution operators may own and operate core DG and/or DS. Edge resources interface to the TSO through DSO only. No tier bypassing exists.

Stack Models

Figure 33 shows the grid stack model with LEN structure. For the case where buildings interact with the grid, Figure 30 shows the extended (triple) stack model. This model defines the need for coordination between the DSO and building management systems. While the diagram depicts this as a direct interface, in practice that would not be scalable. The buildings must interface via the Laminar coordination structure, just as other edge resources do and must coordinate at the LEN level or lower. For situations where multiple buildings are being energy managed by a third party, the BMS in the stack is replaced by the remote management system. The internal structure of the building does not have to be organized as shown in either case, but the Laminar structure can be extended into the building if desired.

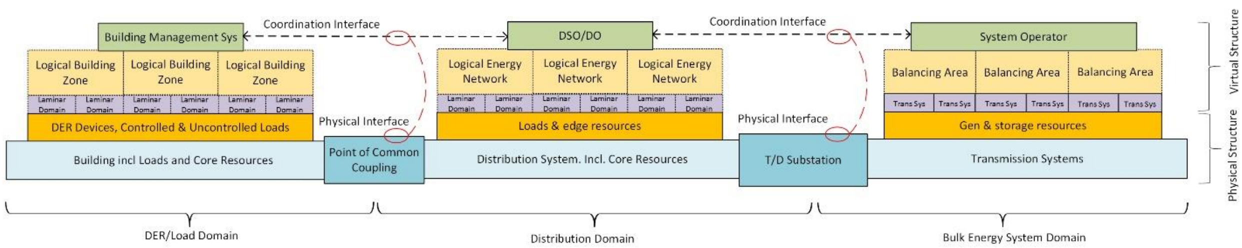

Figure 33 Triple Stack Model for New Grid Structure with Buildings

Similarly, microgrids may interact with the grid. Figure 34 illustrates the triple stack model for microgrids, which is essentially the same as for buildings. Again, the Laminar structure does not have to be implemented inside the microgrid, but can be if desired.

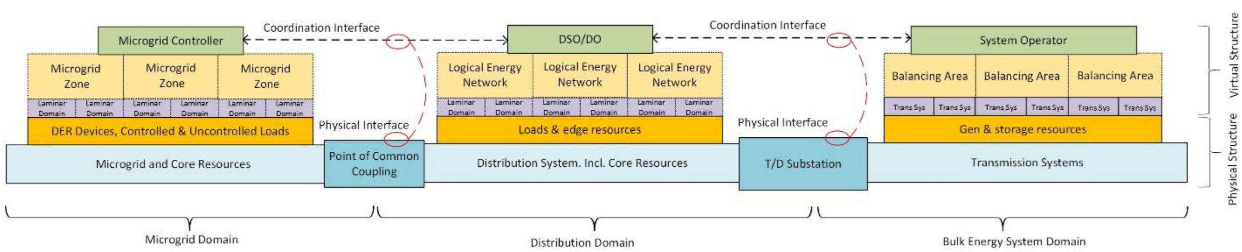

Figure 34 Triple Stack Structure with Microgrids

These two stack models are essentially identical and so from a coordination standpoint microgrids and buildings are treated in the same manner. In general, any DER can be treated this way, so distribution-connected merchant DG or DS, solar gardens, etc. can be handled in the same manner as buildings and microgrids.

Composite Coordination/Control/Communications View

Figure 35 depicts a composite view of coordination, control, and communication employing the structures detailed above.

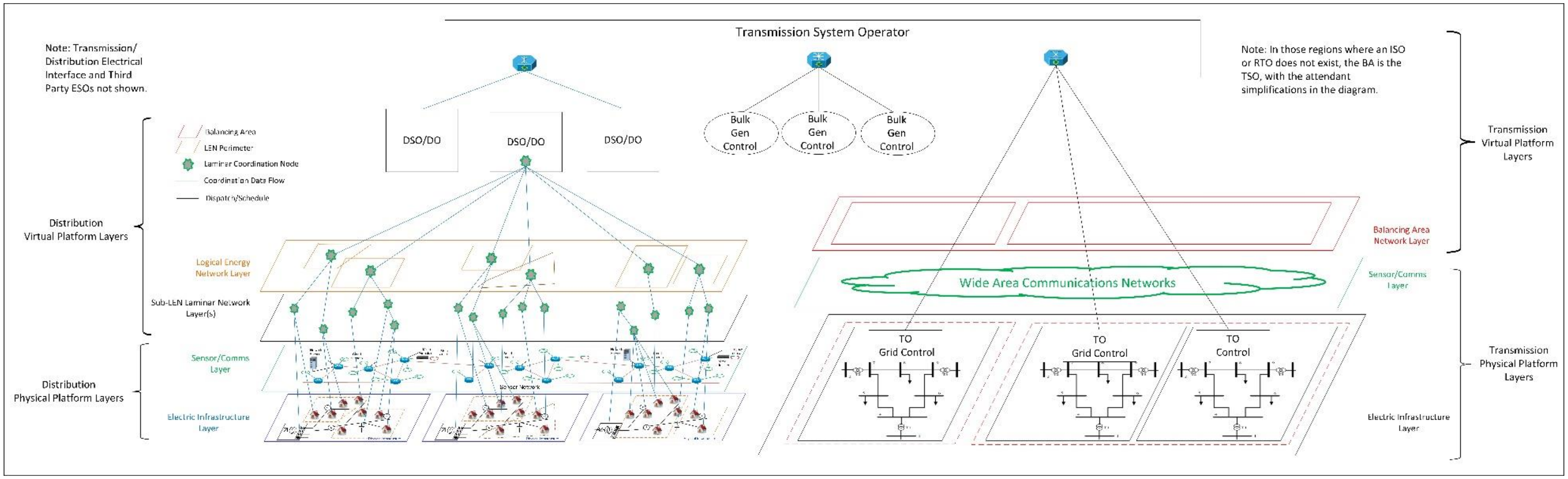

Figure 35 Composite View of New Grid Structure Coordination, Control, and Communication

In the present (20th Century) grid structure, the TSO deals directly with two groups: the generators and the transmissions systems. As DER have become available, means to make use of them at the bulk system level have evolved, usually within ad hoc structures that have poor characteristics from an architectural standpoint. By adding the DSO/LEN/Laminar structure, DER can be systematically and effectively employed at both the bulk system and distribution levels in a standardized way that avoids tier bypassing, and hidden coupling, and provides better structure within which to manage scaling and cyber security issues.

The DSO/LEN/Laminar structure provides a regularized way to manage DER, regardless of how it is geographically dispersed, so that the TSO does not have to be limited to treating DER as if it existed at load aggregation points and without having to have detailed distribution grid state information. The DO does not have to deal with bypassing by the TSO and can thus ensure that use of DER does not conflict with distribution level reliability objectives. The interfaces between TSO and DSOs are far fewer in number than the potential number of DER devices, and there is no direct communication path from edge-connected (and internet-connected) DER to the TSO.

Relationship of ESOs to DSO

Energy Services Organizations such as DER aggregators and remote building managers do not have a structured relationship with DER and the electric distribution providers. Many ESOs may operate in a given distribution service area and they find DER clients in ways that bear little or no relationship to electric system physical or virtual structure. Consequently, they may be interpenetrated in terms of service areas, and may have DER clients scattered across many Laminar Domains, LENs, or even across many distribution systems. Figure 36 shows some of the logical data flow paths that may exist with ESOs.

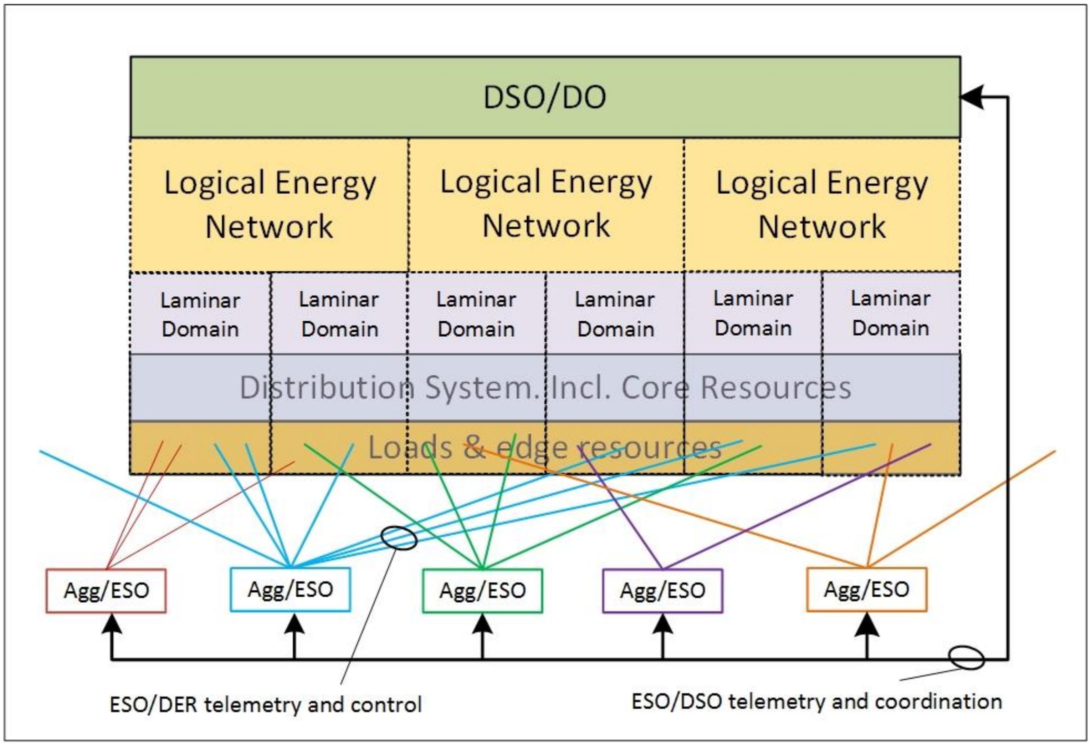

Figure 36 ESO Connection to DER and DSO/DO

ESOs will exist and operate according to their business models. Electric utilities can manage the interactions via Grid Codes and ESOs can provide value to the DER owners and utilities by:

- Completing the coordination framework paths for utilities and edge resources
- Handling the interfaces to DERs and even hosting coordination nodes on behalf of edge resources

The existence of ESOs is a structural constraint that must be addressed in this or any other grid architecture because architecture is agnostic to business models and therefore does not rule out a business model just because it would simplify the architecture. In this case while the ESOs represent a structural constraint, they can also provide useful functionality and assist with scalability of the coordination network.

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 37 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 US presents an opportunity to structure regional resilience into the combined system.

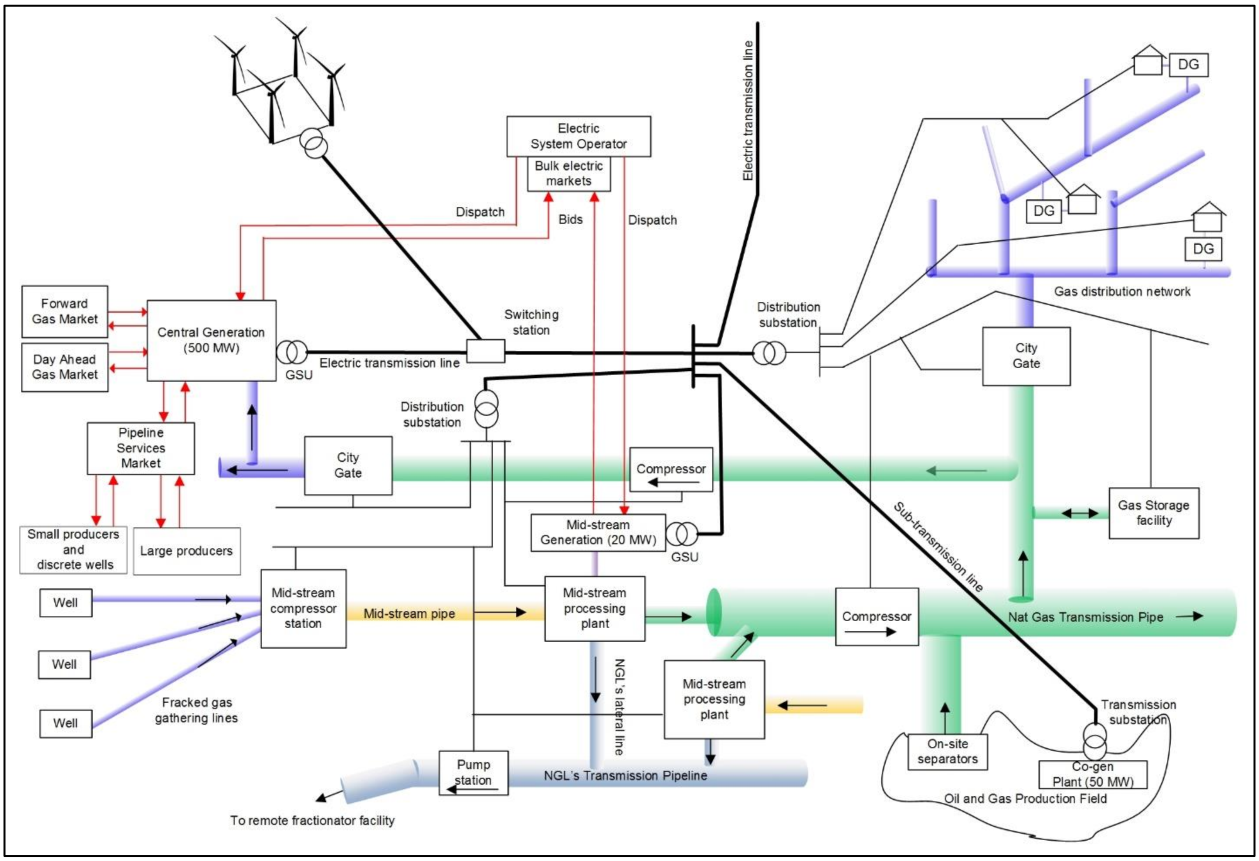

Figure 37 Combine3d Electric-Gas System Structure Illustration

Figure 38 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.

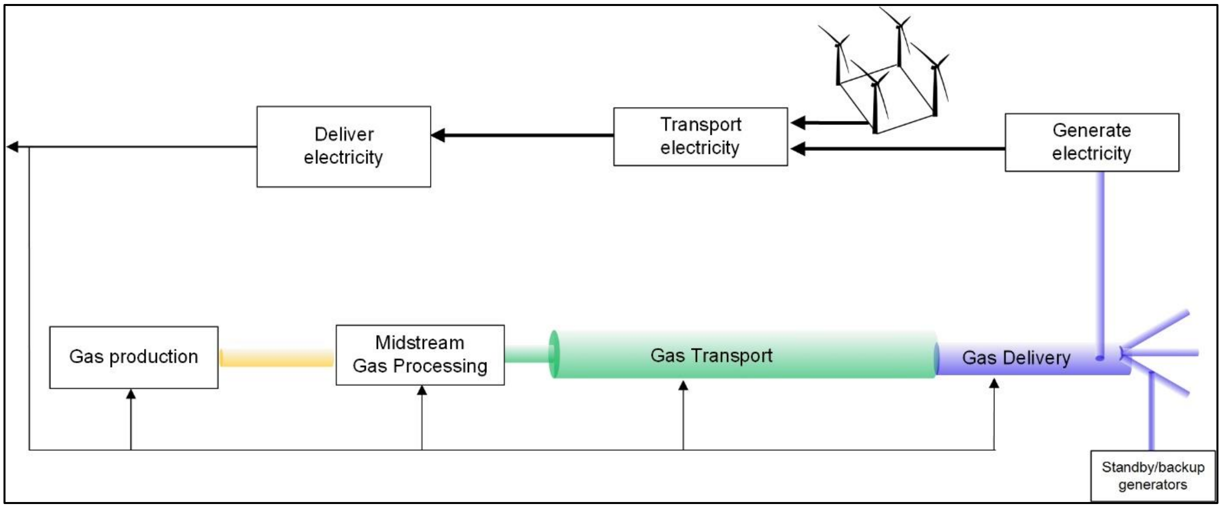

Figure 38 Essential Gas-Electric Interdependency Loop

Now consider the situation with fracked gas in Figure 39. 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.

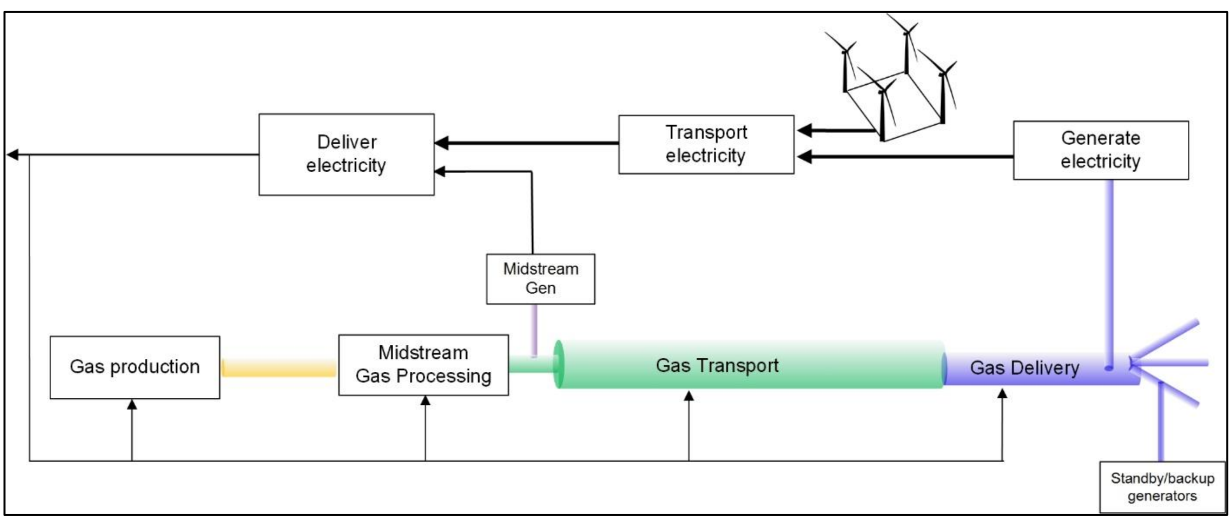

Figure 39 Gas-Electric Inner Resilience Loop

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

Low Head Hydro Distributed Generation

A somewhat related approach to improving bulk energy system resilience is to take advantage of low head hydro to create an array of small distributed generators that connect regionally. These may be in line (run of river) turbines or may be placed at the small dams that are in the regulatory the purview of the Bureau of Reclamation. The concept is not new, but has been considered mostly as a means to augment generation as opposed to being a resilience measure.[39] Aside from the regulatory issues discusses in the footnoted report, the structural issues are:

- Connection to local or regional transmission systems
- Coordination and control in normal operation
- Control during a contingency or "resilience" event

Basic control for small generators of the type envisioned for this are simple and can in fact be nothing more than programmable logic controllers. However, for use as a resilience resource, it would be better to treat a collection of such generators as a secondary or backup generation network, with controls designed to act as nearly autonomously as possible during large outage events and arranged to provide electricity to critical facilities. With this goal in mind, the selection and interconnection of regional arrays of small generators that can operate as backup resources during wide area blackouts and otherwise contribute to baseline generation would provide a third tier of generation (where traditional bulk generation is the first tier and distribution-connected distributed generation and microgrids are the second tier). The control structure would be needed for this third tier does not exist presently but could be based on a version of the Laminar Network coordination approach to operate as either coordinated augmentation of regional first tier bulk generation or as standalone autonomous sub-networks in the event of wide area reliability or resilience events.

This approach would "subimpose" a new structure on the existing bulk energy systems, with backup generation networks connected at the transmission level. The new structure would consist of a number of Resilience Backup Areas (RBAs), each of which has some number of low head hydro generators operating as a regional network. During normal grid operations, these must be accounted for in the balancing process for their respective balancing areas, but in a wide area outage situation, must take on the balancing, load sharing, and frequency and voltage regulation functions for their sub-regions directly. The RBA substructure would not be the same as the structure of the Balancing Authority Areas, as it would be determined by the locations of the low head hydro generators, the critical loads and available interconnections. Such a set of substructures does not presently exist. The RBA system would only operate as such during a massive resilience or reliability event. For ordinary operation, the low head hydro generators would function as part of their respective Balancing Authority Ara resources.

[39] Congressional Research Service, Small Hydro and Low-Head Hydro Power Technologies and Prospects, R41089, March 2010, available online: https://www.everycrsreport.com/files/20100301_R41089_6e8c9c43d2560ac6e10a1372dbcdaadc4f934e48.pdf

Version History

Action	Date	Description	Author(s)
created	10/25/2018	Originated as the 1.2.1 high resilience architecture specification top level document	GMLC 1.2.1 team
V0.4	1/14/2019	Updated grid structure ER diagrams and added data architecture section; resolved citation references.	GMLC 1.2.1 team
V0.6	2/7/2019	Added discussion of low head hydro generation	GMLC 1.2.1 team

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