Grid Architecture Specification: High DER/DA/STO Reference Architecture

GMLC 1.2.1 v0.3

December 2019

JD Taft
S Widergren
A Shankar
R Melton
B Kelley

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JD Taft[1]
A Shankar[2]
B Kelley[3]
S Widergren[1]
R Melton[1]

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[1] Pacific Northwest National Laboratory
[2] Oak Ridge National Laboratory
[3] Lawrence Livermore National Laboratory

Grid Architecture Specification

View Designation: GMLC 1.2.1 High DER/DA/STO Reference Grid Architecture v0.3

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

Summary Overview

This document describes architectural (structural) elements for an electric power system with high penetrations of Distributed Energy Resources, Distribution Automation and, and optionally, extensive grid storage.

Glossary

ARP – Address Resolution Protocol

BMS – Building Management System

BPS – Bulk Power System

BTM – Behind the Meter

C&I – Commercial and Industrial

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

DA – Distribution Automation

DO – Distribution Operator

DOS – Denial of Service

DSO – Distribution System Operator

DER – Distributed Energy Resource

DG – Distributed Generation

DS – Distributed Storage

DSN – Distribution Storage Networks

EE – Energy Efficiency

E-R – Entity-Relationship

ESO – Energy Services Organization

FAN – Field Area Network

FCAPS – Fault, Configuration, Administration, Performance, Security

FERC – Federal Energy Regulatory Commission

FLISR – Fault Location, Isolation, and Service Restoration

G&T – Generation and Transmission

GDOI – Group Domain of Interpretation

GPS – Global Positioning System

MAC – Media Access Control

MPLS – Multi Protocol Label Switching

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

NWA – Non-Wires Alternatives

PFC – Power Flow Controller

PMU – Phasor Measurement Unit

PIM – Protocol Independent Multicast

PTP – Precision Timing Protocol (IEEE 1588)

PTP TC – Precision Timing Protocol Transparent Clocks

PTP BC – Precision Timing Protocol Boundary Clocks

PV – photovoltaic, e.g. solar electric generation

SSM – Source Specific Multicast

QoS – Quality of Service

SUDI – Secure Unique Device Identifier

T/D – Transmission/Distribution

TEDS – Transducer Electronic Data Sheets

TSO – Transmission System Operator

ULS – Ultra Large Scale

VLAN – Virtual Local Area Network

VPN – Virtual Private Network

V/VAR – Volt / Volt Amperes Reactive

WAN – Wide Area Network

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

The 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.

Scenarios and Point of View

The key scenarios for this reference architecture are:

- High penetration of (meaning more than 50% of feeder power sourced from) DER
- High levels of deployed Distribution Automation (20% or mode of distribution feeders have advanced sensing, measurement, protection, and control), with a subset of high penetration of power electronics for grid control functions (flow control, regulation, stabilization, and synchronization)
- Ubiquitous penetration of grid energy storage, with two subsets: high penetration of grid-embedded storage (owned/operated by electric utilities) with no consideration for behind-the-meter storage; high penetration of BTM storage with no significant utility or grid-embedded storage
- High penetration (more that 50% of vehicles in use) of electric vehicles and vehicle chargers
- Buildings and microgrids acting as grid resources (providing grid services)

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 is 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*.

Objectives

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. The qualities of Delivery, Adaptivity, and Enablement are especially relevant to this reference architecture. Specifically, the overall objective for this reference architecture is to show how to modify existing grid structure and specify new grid structure as appropriate to enable the grid to accommodate and make use of DER and to incorporate DA.

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

1. Facilitate the increasing penetration of DER and enable its use for customer and system benefit. Accommodate DER that may exist in dynamic heterogeneous mixtures that vary across a system with multiple models of DER use, ownership, and operation.
2. Enable development of ad hoc microgrids or other consumer-driven arrangements.
3. Enable improved electric system reliability and resilience by automating grid operations and responses.
4. Enable creative uses of and access to DER assets and enable new business models for the grid, such as use of DER for NWA, network energy economy models, etc.
5. Provide industry structure models that allow exploration of new regulatory approaches that relieve constraints on the use of DER; redefine Bulk Power System and Distribution System relationships to improve system operation and economic efficiency.

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

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 Advanced Bulk Power System Architecture Principles

1. For operational purposes, DER includes DG, DR, and DS, but not EE. Microgrids count as DER.
2. From the *grid point of view*, buildings and microgrids look the same. Each may be capable of supplying services to the grid.
3. Standardize interface types between the grid and edge-connected device and systems and keep the number of such interface types as small as possible.
4. Provide flexibility and granularity in grid structures for DER and DA (scalability for DER penetration, reconfigurabilty of grid for DA).
5. DER types may be intermingled at any scale; mixes may be dynamic and may vary across a single distribution system. Accommodate dynamic DER mixes, groupings, and grid connections.
6. Grid structure should enable DER provide multiple benefits to the grid if it can to the extent practical.
7. For utility–owned DER, grid structure should support flexible placement.
8. DER should be able to work with a Bulk Power System or Distribution System or more local operational control groupings as desired by users and operators.
9. Grid structure should enable autonomous operation or cooperation/joint operation of DER with peers.
10. Coordination structure must be able to merge electrical physics with economic or other coordination mechanisms (i.e., don't decouple markets from physical systems).

General Architecture Principles

1. A good architecture is one that meets the needs of the stakeholders (especially the users) to their satisfaction, does not violate established principles of system architecture, and takes into account the relevant qualities and properties as the stakeholders require.
2. Good architectures have conceptual integrity (adhering to a set of core principles, clean of unnecessary complexities or 'exceptions,' similar problems are solved in similar ways, etc.).
3. Conceptual integrity is best achieved by a small cohesive team of like-minded architects. Architecture should be the product of a single architect or small team with an identified leader.
4. Essential functionality drives complexity, not architectural "elegance."
5. Architectural structures should have formal bases where possible to minimize ad hoc configurations with unknown properties.

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

Core Architectural Concepts

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

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

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

Flexibility, extensibility, and agility – the ability of a system (in this case the grid) to make (usually automatic) adjustments to grid stresses. This can include traditional energy resource flexibility, and increasingly, energy resource flexibility afforded by the use of DER, including net load flexibility. It 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.

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

[6] Mark Klein, Linda Northrop, et al., Ultra-Large-Scale Systems, Software Engineering Institute, Carnegie-Mellon University, 2006, available online: https://resources.sei.cmu.edu/asset_files/Book/2006_014_001_635801.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 refers to 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. 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.

Grid energy storage as a core grid 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 operations. When applied at the distribution level, such decoupling is bidirectional, meaning that volatility arising at the Bulk Power System (BPS) level can be decoupled from the distribution system and loads; volatility at the distribution edge arising from DER can be decoupled from the BPS. There are operational advantages to both types of decoupling. Generally, the use of grid energy storage at the electric distribution level as a core grid component relates to a range of operational functions, as opposed to BPS grid services.

These operational functions include:

- Regulation and Stabilization
- Outage Ride-through
- Black Start Support
- Volatility Management
- Distribution Flow Management Support
- System Integrity Remediation
- Mitigation of the Need for Secondary Load Control
- DER capacity management
- Generator black start
- Defense against edge-based volatility attacks
- System agility improvement

Distributed and mixed entity coordination/control – control of DER, especially grid connected inverters, must fit into a structure that allows for mixtures of DER, for control of DER by various entities besides the distribution utility, and for interpenetration of DER types and entities (e.g. multiple DER aggregators operating in overlapping areas down to the distribution circuit secondary level), as well as direct control by the distribution utility. Communication with the DER elements for purpose of control may be through utility communication networks or through telecommunications service providers and may include the internet. All of these modes of communication and control may co-exist in a single utility service area. In addition to control via an external entity, control may be performed autonomously by any particular DER element or groups of DER elements may associate and operate as coordinated DER networks, either under supervision by an external entity or as an autonomous system. Distribution Automation systems may operate in similar autonomous unit or coordinated autonomous group modes.

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

Sensing/measurement infrastructure layer – sensing and communications for the distribution grid must be structured as an infrastructure layer rather than a set of application silos.[7]

Architecture Specifications

The architectural views are presented in terms of (black box) components, structures, and externally visible characteristics.[8] 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 – Storage v0.2

Grid Architecture Component Class Specification – Microgrid v0.1

Grid Architecture Component Class Specification – Digital Communications Network v0.1

Grid Architecture Component Class Specification – Grid Sensor v0.2

Grid Architecture Component Class Specification – Inverter

Grid Architecture Component Class Specification – Load

Grid Architecture Component Class Specification – Power Flow Controller

Grid Architecture Component Class Specification – Solar PV

Grid Architecture Component Class Specification – Electric Vehicle

Grid Architecture Component Class Specification – Electric Vehicle Charger

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.

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

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

Baseline E-R Model

The diagram in Figure 1 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,[9] so this schema is a useful "starting point" representation. The specifications below will describe a model reference grid architecture with a focus on DER, distribution automation and storage integration for electric distribution systems. That will provide the "ending point" representation.

[9] 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

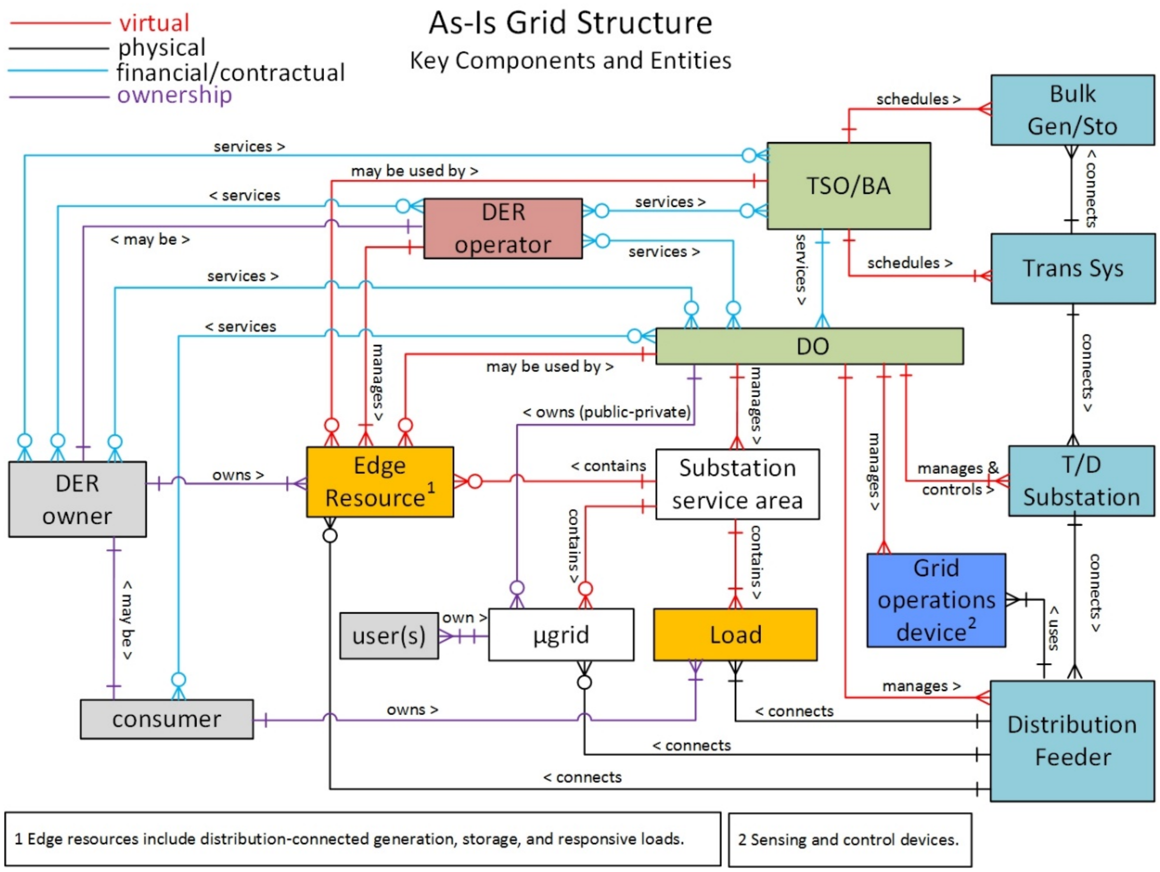

Figure 1 Existing Grid E-R Structure Diagram

The stack diagram in Figure 2 is an alternate representation of the same system. In this depiction, the grid is viewed as comprising two primary domains: the Bulk Power System domain and the distribution domain.[10] This model emphasizes the similarities and differences in gross organization structure (not physical infrastructure) will be used to enhance the partial homology[11] that exists now to derive a new structure that enables DER /storage integration and distribution automation.

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[10] See Visio file *high DER DA Sto arch drawings v1.1.vsdx* for extended stack models with non-utility domains (buildings, microgrids, DER).

[11] In the biological sense of structural correspondence.

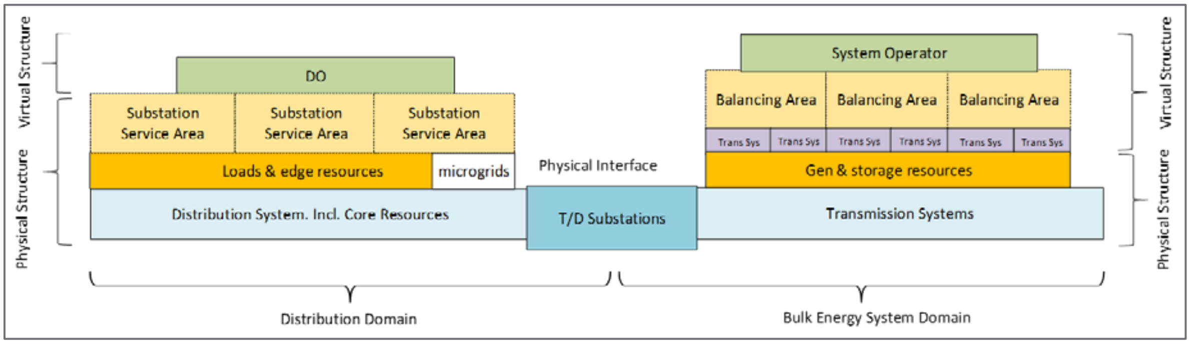

Figure 2 Existing Grid Stack Model

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: Distribution Role Evolution

The Transmission/Distribution coordination architecture can be structured as shown in Figure 3. The purpose of this structure (also called the Market DSO model) is to provide a clean interface and separation of roles and responsibilities for Distribution Operators and Transmission System Operators. This enables the TSO to use distribution connected assets (DER) for grid resilience and operational flexibility purposes without interfering with distribution operations or distribution system reliability. 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.

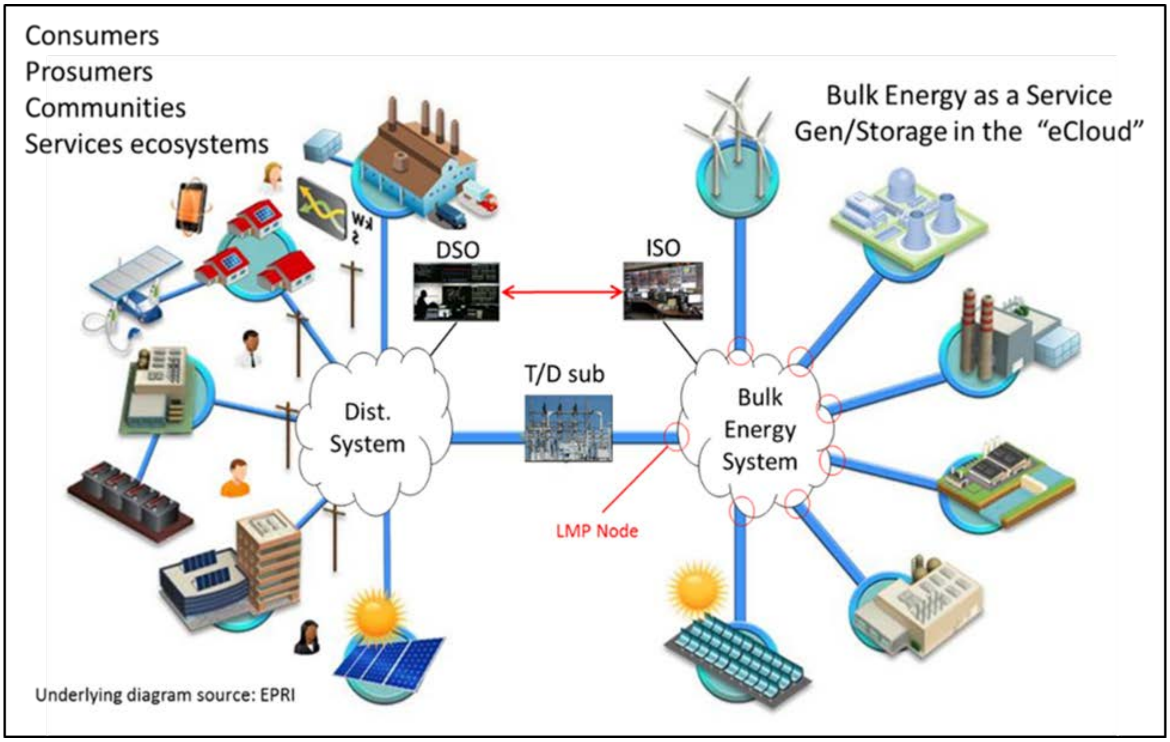

Figure 3 Total DSO/TSO Industry Structure Model

Note that from the perspective of the distribution operator, a Bulk Power System looks like a resource the DSO can manage in addition to its own distributed energy resources. A clean interface is provided, where energy and services can be exchanged. This is a fundamental change from traditional BPS structure and operational models but is necessitated by changes happening at the distribution level. A significant and useful consequence of this model is that the distribution operator handles all information exchange at the interface and does not have to supply detailed internal state information to the TSO. It resolves the issue of potential collisions over distribution reliability responsibility vs. tier-bypassing and hidden coupling-induced reliability problems. This structure thereby benefits both the transmission system operator and the distribution operator.

This industry structure introduces a new interface: the DSO/TSO interface (indicated by the red double ended arrow in Figure 3). 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 flowing across this interface includes:

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 having third parties on one end.

A consequence of this specification is that DER telemetry flows and dispatch instruction flows have a structure shown in Figure 4, where the lines indicate bidirectional data flow paths.

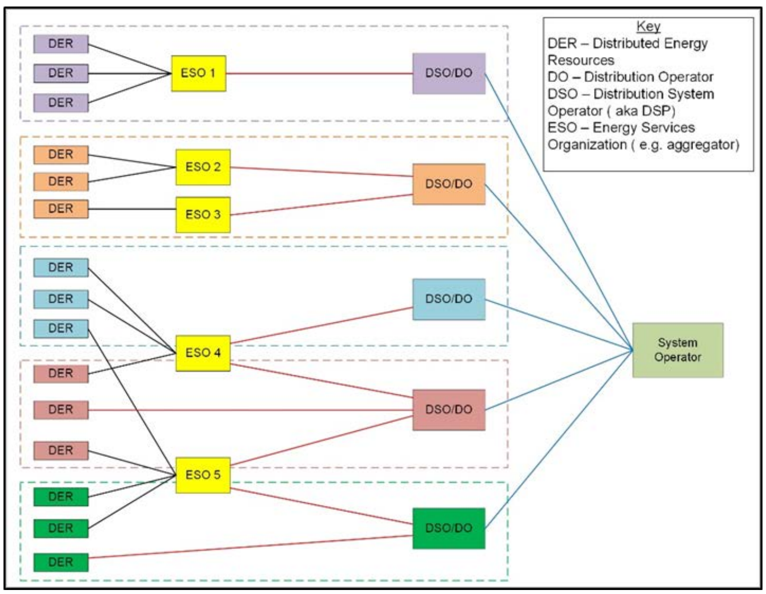

Figure 4 Multi-DSO DER Telemetry Flows

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.

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.

If distribution systems should evolve into platforms or networks for more general peer-to-peer energy transactions (which would require the elimination of Net Energy Metering), then the DSO's role would include management of the network in a more general way, to include:

- internal power wheeling
- local interchange
- power flow scheduling
- network congestion management

in addition to the usual reliability functions. Later specifications such as the LEN model support these potential new roles.

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 Power 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.

Specification 2: Flow Control and Regulation via Power Electronics in Distribution Grids

In a traditional distribution grid, power flow control and voltage regulation are accomplished by utility-owned devices, such as distribution substation transformer load tap changers, feeder step voltage regulators, and fixed or adjustable capacitor banks. These devices are located in medium-voltage distribution grids, are typically mechanical switch based, and exhibit slow response and limited lifetime. Volt/VAR optimization and control is normally performed on a centralized day-ahead basis, using forecasted loads, SCADA data, and a network model. With increasing distribution (feeder) automation (DA) and power electronics based distributed energy resources (DER), e.g. solar photovoltaic and energy storage (ES) systems, distribution grids have gradually evolved into high penetration DER/ES/DA scenarios. Distribution grid structure and control methodology are changing accordingly. New control devices appear in both medium-voltage grid zones, low-voltage grid zones, and their connection points, i.e. from medium voltage to low voltage.

2.1 New power flow control and voltage regulation devices

New power electronics-based power flow control devices are emerging due to provide fast response, flexibility, and efficiency. A power flow controller (PFC) is defined as a functional block which comprises power electronic converter(s) and its embedded control hardware board (typically with DSP, FPGA, ADC, DAC, RAM, communication ports, etc.), as illustrated in Figure 5. Functionally, a PFC device controls the power (both real/active and reactive power quantities and directions), which flow through the power lines. With power electronics, it is also possible to control the electrical waveforms (e.g. from dc to ac), meet harmonic requirements, control the power extraction from the prime mover sources, control output ac frequency, and control output voltage or current magnitude.

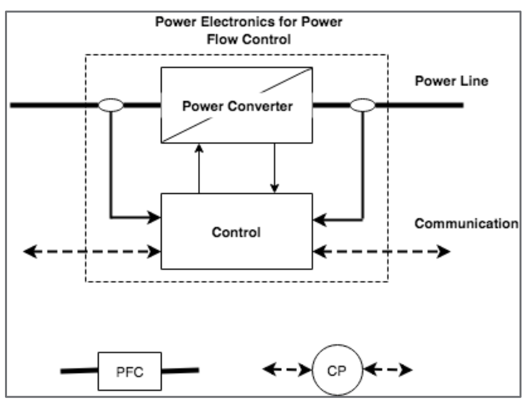

Figure 5 Internal hardware structure of a power flow controller

The power flow control function exists essentially in all power electronics for grid applications, including HVDC, MVDC, FACTS (SVC, STATCOM, UPFC, UPQC, etc.), and DER (including solar PV, energy storage, direct-drive wind turbine, micro turbine, fuel-cell, small hydro, reactive source, etc.). Hereafter, we treat power electronics converters as common elements in a terms function, representing the physical hardware device and control point (CP) as denoted in Figure 6. In addition, we denote a PFC between the DER and the grid as Type-1 PFC, and a PFC in-between two grids or portions of one grid as Type-2 PFC.

Figure 6 Two General Configurations of Power Flow Controllers

Examples of Type-1 PFCs are solar PV inverters or smart inverters,[12] which perform advanced control functions and grid services (supporting grid or even forming grid) beyond basic grid feeding function). Examples of Type-2 PFCs are D-STATCOM, UPQC, and solid-state transformers or substations.

2.2 Feeder segmentation in logical energy networks

With high DER/ES/DA, it opens the possibility to create resilient distribution grid architectures that could be different from conventional radial unidirectional power flow architecture.

Structure 1: Feeder segmentation and multi-microgrid network

Individual feeders A(or even individual phases) can be partitioned or segmented into multiple virtual control areas or microgrids for autonomous power balancing, thanks to the availability of DERs. Between two neighboring segmentation, the PFC device can be “inserted” to electrically decouple their individual operations and to control tie-line power flow. This concept is illustrated in Figure 7.

[12] Y Xue et al., On a Future for Smart Inverters and Integrated System Functions, December 2018, available via the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

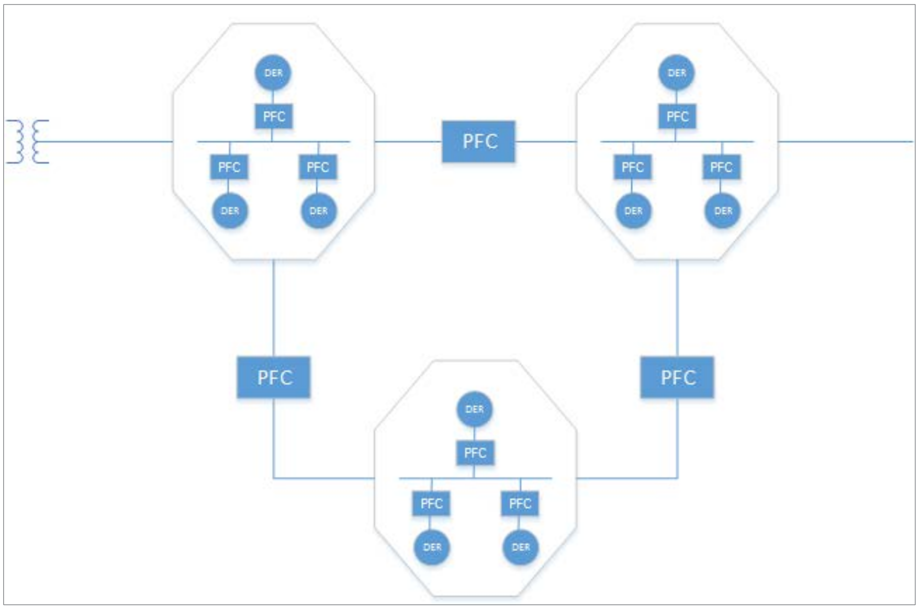

Figure 7 Distribution Feeder Segmentation

Structure 2: Meshed distribution network

Similar to transmission grid, meshed networks can be formulated to improve distribution grid resilience. A simple 3-bus network is shown in Figure 8.

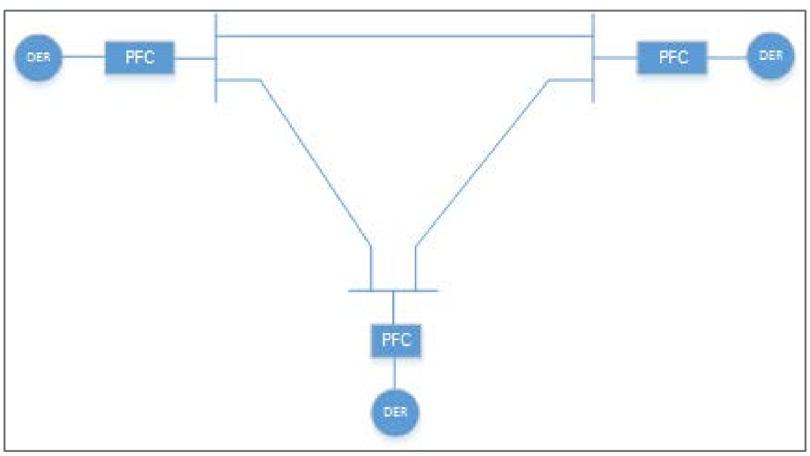

Figure 8 Simple 3-bus Meshed Distribution Network

2.3 Collaborative Controller Network (CCN)

The control methodology for high DER/ES/DA distribution grid may shift toward a more distributed structure, given significant increase of control points and time-critical control requirements. The CCN[13] offers a structural approach for high penetration DER/ES/DA grid architecture scenario. Figure 9 shows an example data/control message flow structure for a CCN.

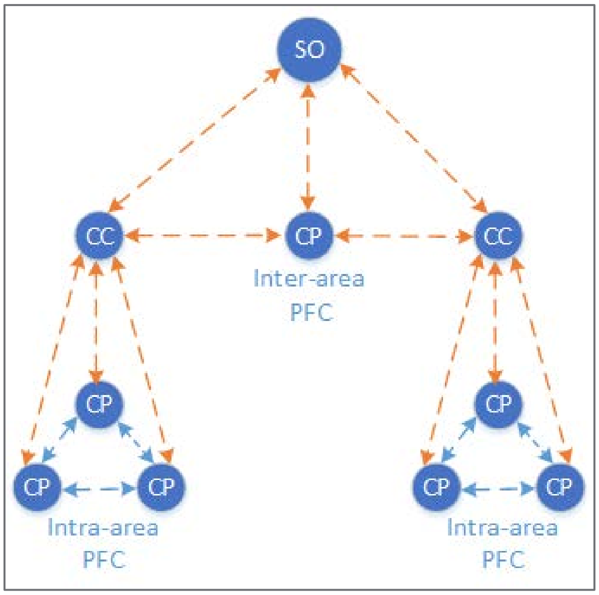

Figure 9 Collaborative Controller Network

In a CCN, individual control points associated with individual PFCs may only communicate with neighboring control points to perform iterative distributed optimization and control algorithms to detect topological or structural changes and dynamically converge to global optimal control solutions.

[13] Y Xue and M Shankar, High DER/DA/Storage Architecture Circuit Structure and Power Flow Control, PowerPoint presentation, ORNL, March 2019.

2.4 Volt/VAR Regulation

Traditional distribution Volt/VAR regulation is performed with a combination of centralized (substation transformer LTC) and slightly decentralized (feeder primary capacitor) means. As solar PV penetration increases, voltage volatility at the edge increases significantly, making these methods ineffective. Increasing the size of components does not help much. Instead a change of structure is called for. By applying Volt/VAR regulation locally on distribution secondaries (via power electronics), effective regulation is possible. This works because the power electronics device uses storage to buffer the local volatilities cause by solar fluctuations.

Specification 2 details:

2.1 Use PFCs to decouple DERs from the grid where possible.

2.2 Insert PFCs to partition feeders into multiple virtual control areas for autonomous power balancing.

2.3 Implement control methodology through peering of CPs.

2.4 Deploy CCN concept to overlay across CPs.

2.5 CPs communicate only with peer neighboring CPs.

2.6 Use decentralized Volt/VAR regulation on distribution secondaries in preference to traditional methods when distributed solar PV is prevalent.

Specification 3: 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 10 shows a commonly used structure for electric distribution utility sensing and control.

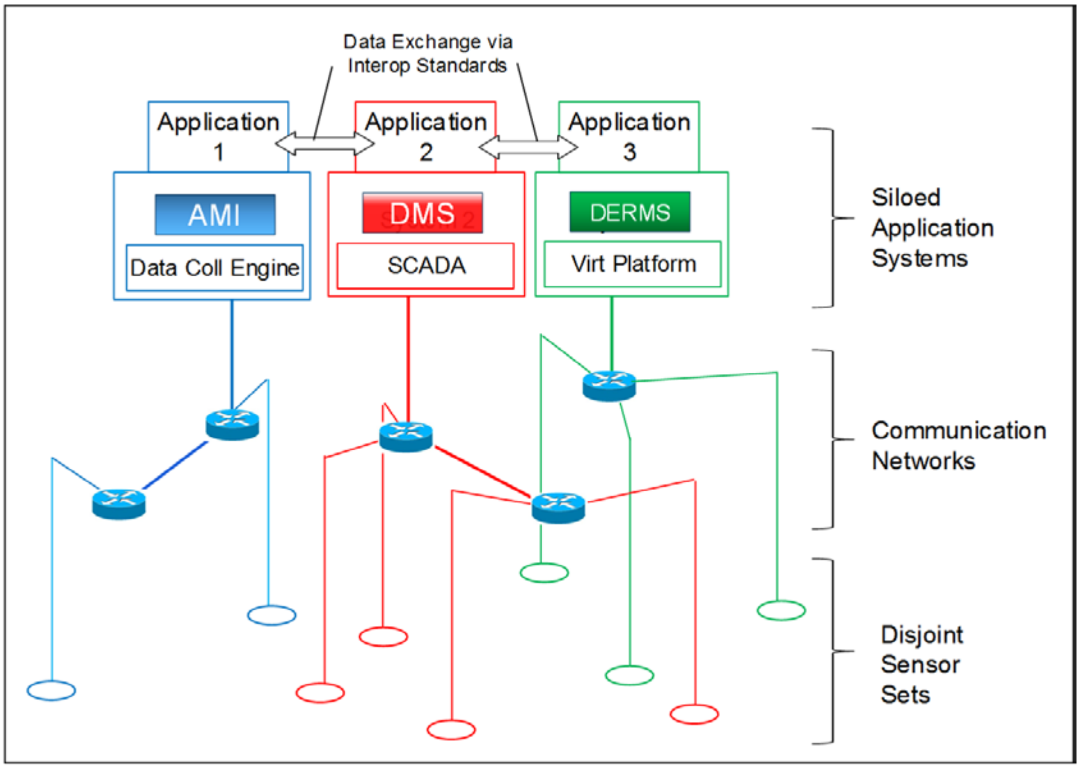

Figure 10 Siloed System Structure Results in System Brittleness (Anti-resilience)

This multiple vertical silo structure is expensive due to back-end integration costs and is anti-resilient due to that same 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 attempt to simplify the integration problem but *cannot address the anti-resilience issue, which is fundamental to this structure.*

Figure 11 illustrates the layering and consequent decoupling of applications that limits brittleness and enhances configurability, functional flexibility, and functional extensibility.[14]

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

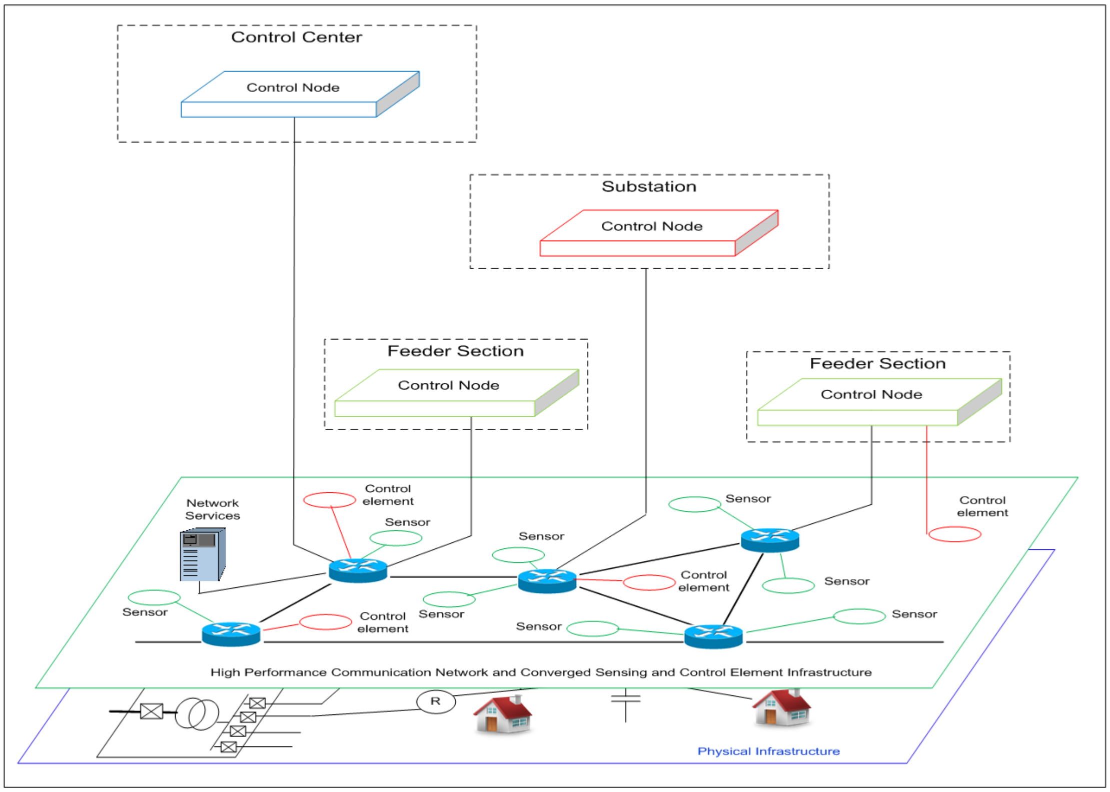

Figure 11 Sensor Communications Layer Structure

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 12.

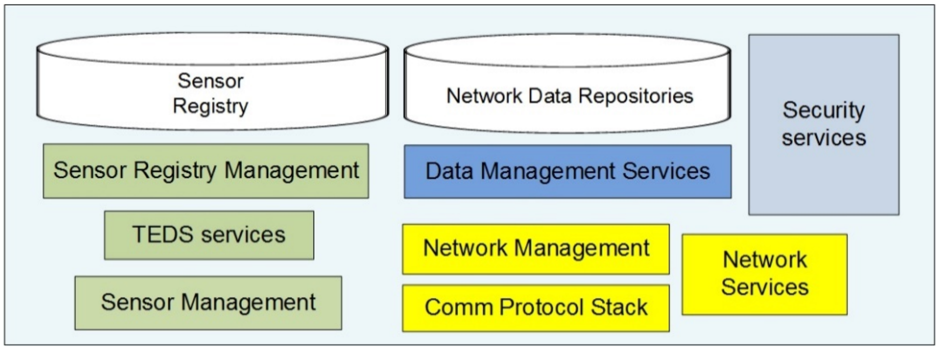

Figure 12 Sensor/Communications Infrastructure Layer Functions

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[15] refers to Transducer Electronic Data Sheets.

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

Specification 3 details:

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

3.2 Make the communications network a full services IP network. In particular, provide streaming protocols so that the network can function as a distributed, access-controlled publish/subscribe mechanism.

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

3.4 Combine the electric distribution layer and the sensor/communications layer to form a distribution platform. Use this platform with the items from 3.2 to manage sensor data flows.

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

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

3.7 Circuit electrical control devices may be included in the sensing/communications layer of the platform.

Specification 4: Storage

This section presumes that bulk electric grid storage costs and performance improve to the point where storage can be deployed widely in the grid and given that hypothesis, considers grid structure and operation when storage is ubiquitous as core grid infrastructure. Uses in this scenario include generation/load decoupling (including outage ride-through), volatility export suppression, and even cyber-security improvement.[16] A wide variety of uses for storage have been imagined, including electricity market profit maximization, operational cost minimization, reliability improvement, and distribution level energy loss minimization and various mathematical solutions have been derived for optimal storage unit placement under these criteria.[17] Here we consider storage as a ubiquitous

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[16] 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

[17] Y Tang and S Low, Optimal Placement of Energy Storage in Distribution Networks, December 2016, available online: https://ieeexplore.ieee.org/document/7798759

embedded core grid component whose purpose is mainly to augment grid resilience. Uses of storage for ancillary services and bidding into electricity markets are well-known and are not considered here.

Figure 13 shows three scenarios for the effect of ubiquitous storage on power grids. The top illustration shows grid structure as it stands today, with essentially no internal storage. Generation is controlled to follow load (which may be modified in small amounts via demand response), while renewable generation acts as both a resource and a system disturbance. There is strong coupling between generation and load, which causes a balance problems and results in system brittleness. In the middle diagram, storage in large amounts is used to partially decouple generation and load, resulting in a relaxed coupling and balance problem, with increased flexibility to handle stochastic generation. The third diagram is an extreme case, where massive amounts of storage are used to completely decouple generation from load. In this case, generation is used to fill storage, and storage supports load fully, all the time. There is no balance problem and no need for load frequency control. The primary control problem is State of Charge (SoC) management. The third model is not likely to be implemented before 2030 but serves as an extreme boundary case at the opposite end of the spectrum from the no-storage case.

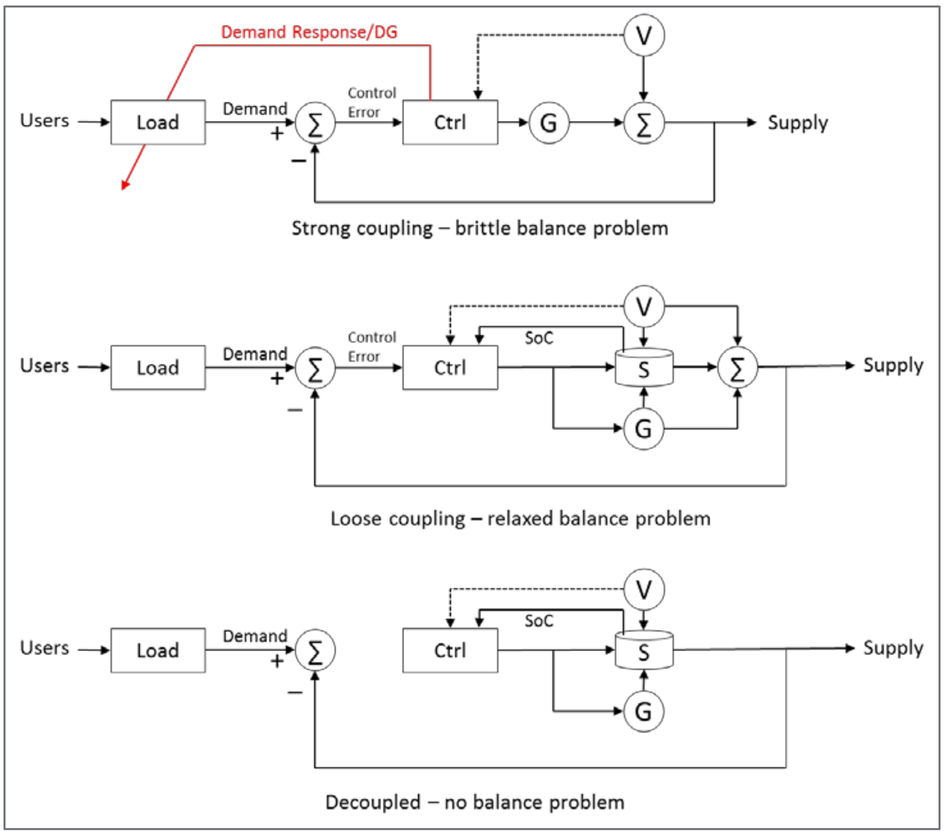


Figure 13 Levels of Decoupling via Large Scale Use of Storage

In section 4.1, the use of ubiquitous storage as core infrastructure is considered. In Section 4.3, a similar scenario for behind-the meter (BTM) storage is considered. These two cases are examined as extremes so as to identify grid structures that can accommodate any time-varying mix of grid and BTM storage.

4.1 Coordinated Storage Networks

See the discussion on this topic in the Advanced Bulk Power Systems Reference Architecture Specification Document, in Specification 5.[18] The resultant specification details are reproduced here.

Specification 4.1 Details

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

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

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

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

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

4.2 Sharing Storage across Distribution Substations

For electric distribution grids, the use of fast bilateral energy storage[19] raises a structural issue, namely how to share storage to the distribution system, under the presumption that storage will not necessarily be placed in every substation. 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

[18] Advanced Bulk Power System Reference Architecture Package, available online: https://gridarchitecture.pnnl.gov/library.aspx

[19] 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.

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.

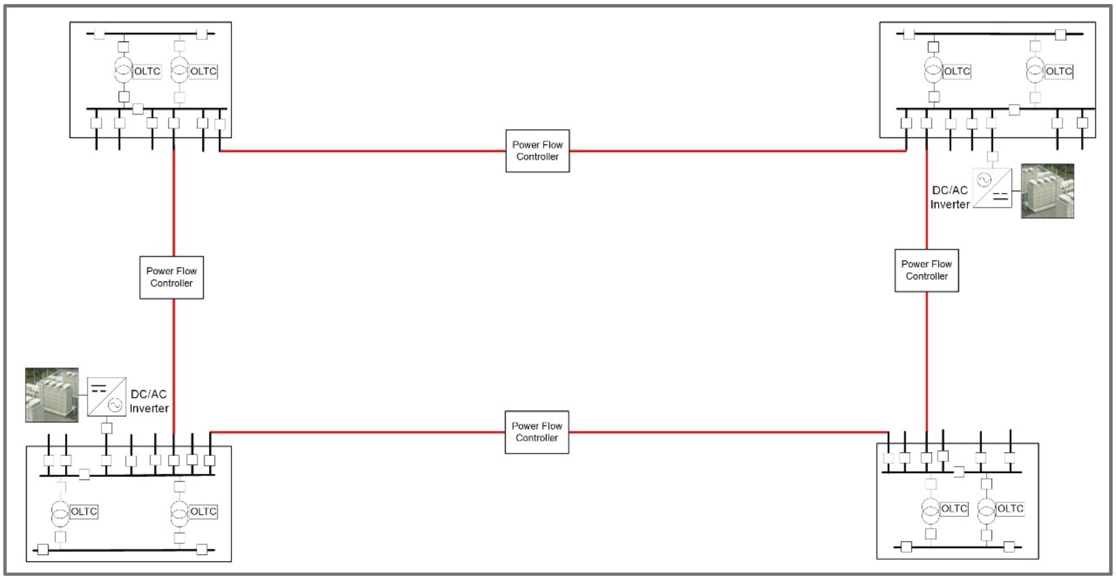


Figure 14 Substation Storage Sharing Ring Structure

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 storage network. 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. 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 3 supports both centralized and distributed operation of the storage networks.

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

- 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.

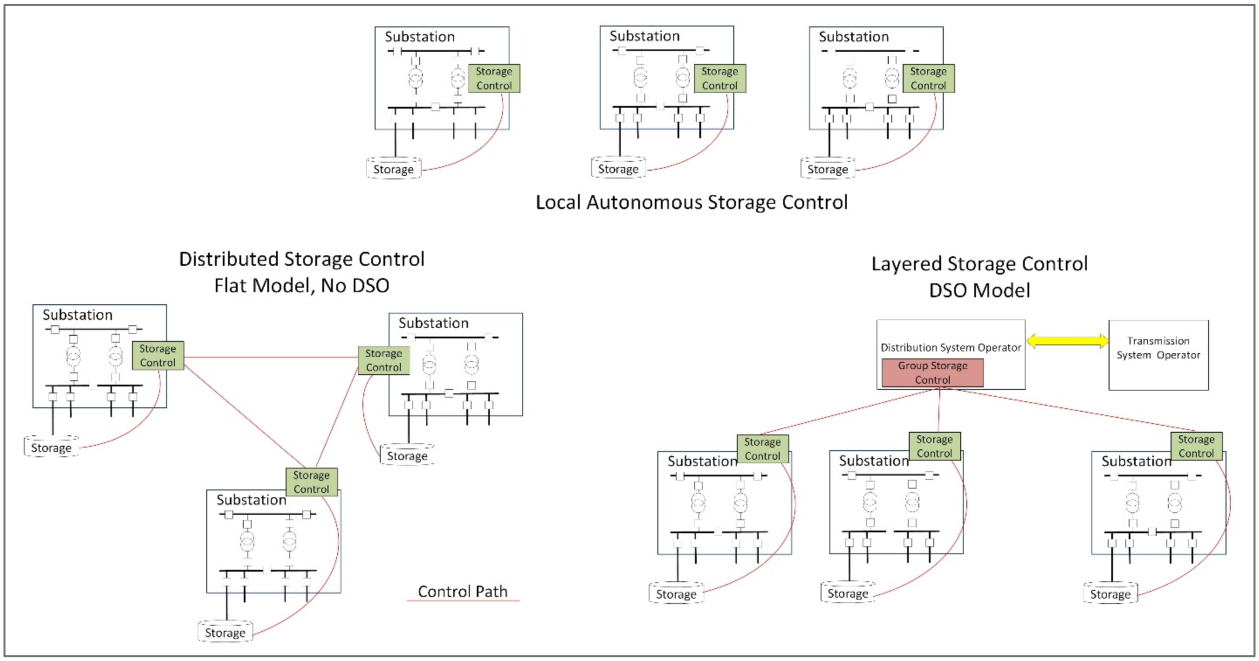


Figure 15 Distribution Storage Network Control Structures

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

Specification 4.2 details:

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

4.2.2. 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.

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

4.2.4. Do not bypass the distribution operator to use storage networks for BPS purposes. Work through the DSO/TSO interface in all cases.

4.3 Behind the Meter Storage

Behind the meter storage presents a different set of constraints than utility owned storage. Key differences include:

- Ownership: BTM storage is customer or third party owned. Boundary deference must be supported by the coordination/control structure
- Location: Typically, on a feeder segment, though for large commercial or industrial customers the storage could be at a private substation
- Size: Range of size, residential storage will typically be on the order of 10's of kilowatt hours[20] with the specific size determined by the intended purpose of the batter storage, for example backup power versus combination with a solar system

With these differences in mind, one can still apply the decoupled, coordinated storage network structure to BTM storage by extending the structure to include all DER BTM.

The resulting structure is shown in 16. In the figure, "Flex DER" includes the various forms of flexible loads, any type of storage may be included, and the presence of solar or other distributed generation noted as DG. This structure presents a uniform interface to the grid and responds to requests for services in a standardized manner whether they come from an aggregator or a DSO.

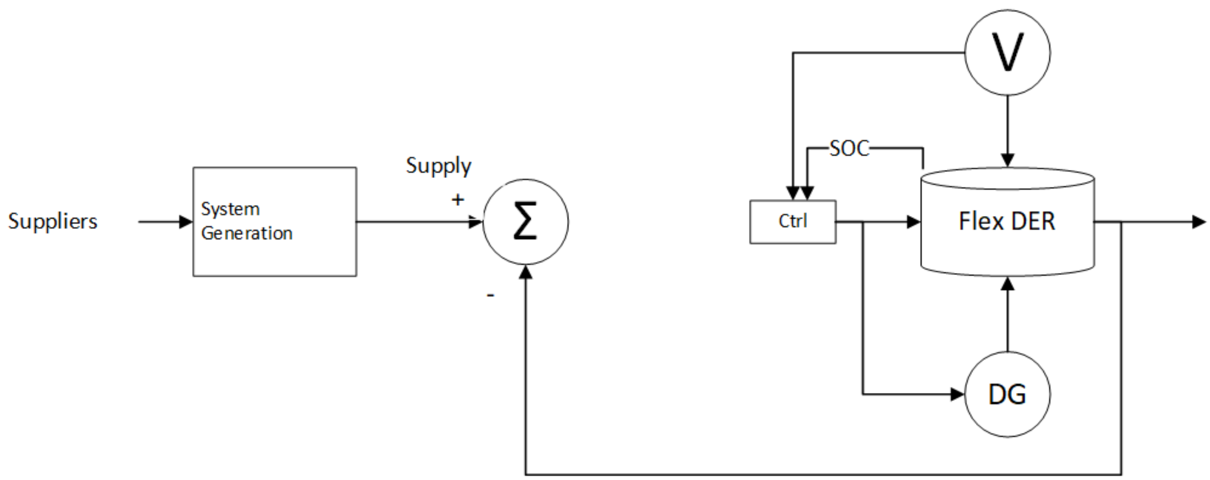


Figure 16 BTM Coordinated DER and Storage Structure

The communication/sensor layer structure depicted in **Error! Reference source not found.** allows for a standardized coordination interface for customer or third-party owned assets thus respecting boundary deference. The structure does not prescribed a specific form of coordination.

[20] According to the EIA in 2017 the average annual residential consumption of electricity was 10,399 kWh. That is 28.4 kWh / day. https://www.eia.gov/tools/faqs/faq.php?id=97&t

Specification 4.3 details:

4.3.1 Consider BTM storage need for boundary deference due to ownership issues

4.3.2 Define a uniform structure for representing BTM storage and other DER

4.3.3 Use a uniform structure that is independent of any specific coordination and control mechanism (resource allocation vs. market method, for example)

Specification 5: 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.[21] The resultant structures are called Laminar Coordination Networks. Figure 17 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).

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.

[21] 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 .

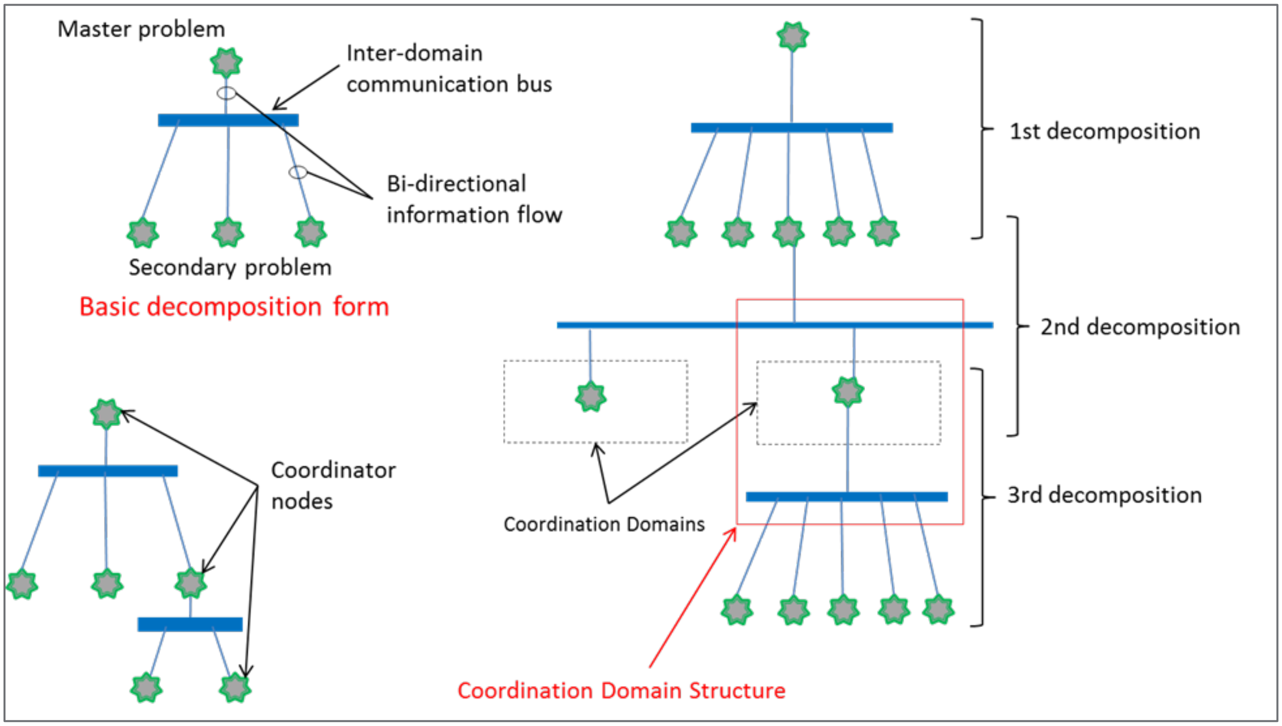


Figure 17 Laminar Coordination Framework Structural Elements

Each Laminar coordination domain contains a Domain Coordination Node, and intra-domain communication bus, any devices to be coordinated, the computing elements (hardware and software) needed for both the Coordination node and the local applications (analytics, control, etc.) and northbound and southbound communication interfaces. Figure 18 shows a logical view of a coordination domain.

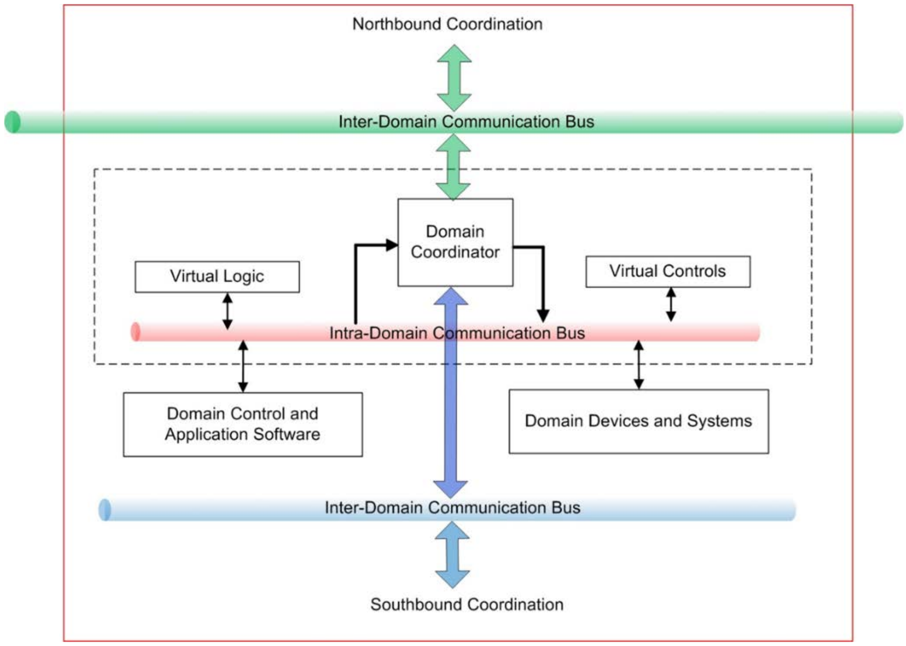


Figure 18 Laminar Coordination Domain Structure

Figure 19 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.

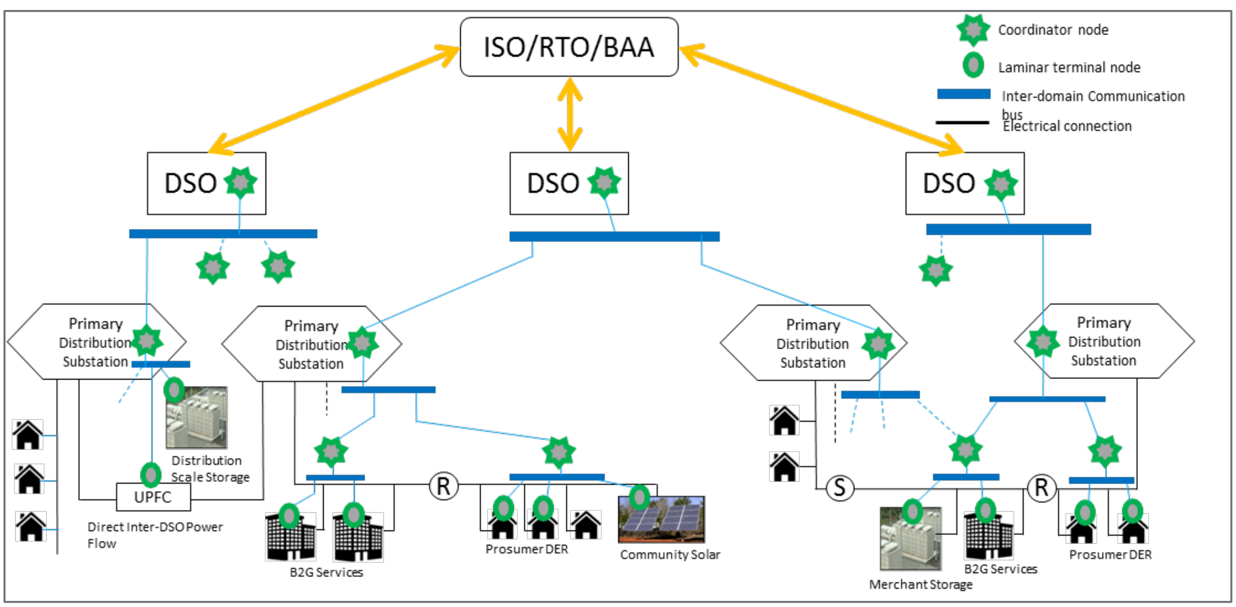
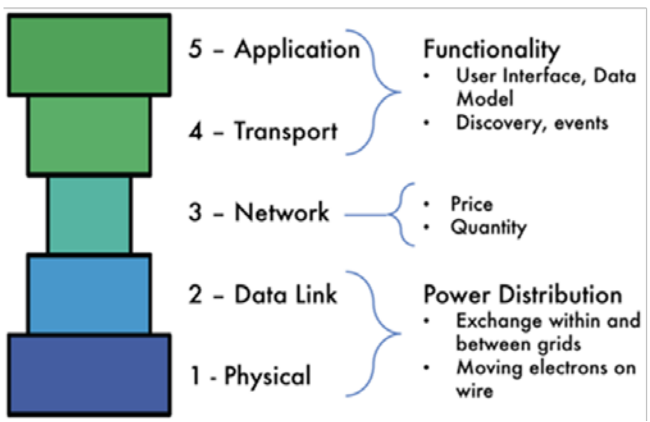


Figure 19 Example Laminar Network

<u>Treatment of Microgrids and Buildings in Laminar Networks</u>

From the perspective of grid structure, buildings and microgrids present similar issues. Each may have loads, storage, and energy sources and be connected to a grid at a point of common coupling. Microgrids can be isolated from the grid ("islanded") but so can buildings, via switchgear and protection. Modern buildings, especially commercial buildings can be quite complex, with a vast array of internal systems and devices.



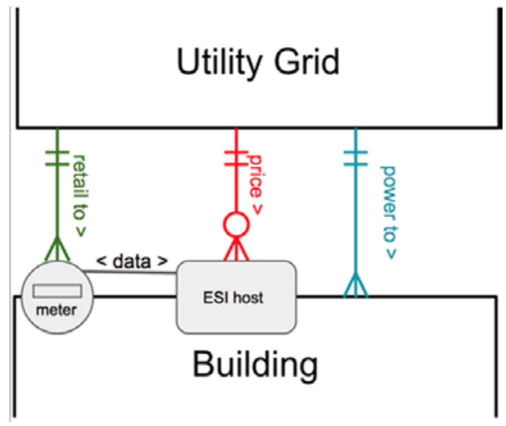


Figure 20 Building-to-Grid Interface Models

For many buildings, there is a building management system, which may be in the building or may be remote. In some cases, third party organizations perform the building energy management and even aggregate various buildings for that purpose. For residential buildings this is not so likely, but some simpler version of energy management such as a NEST thermostat may be present. In some approaches to advanced building control, individual energy consuming devices interact with energy sources including the grid to obtain energy, provide comfort and utility, etc.[22] Figure 20 illustrates a conceptual model for a stack-oriented building-to-grid interface.

From the standpoint of the grid, the layered decomposition model as applied in Specification 1 provides a consistent means to handle exchange of services between building and grid. Essentially, the Building Management System (BMS) plays the role equivalent to the DSO and the distribution system plays the role equivalent to the TSO. In other words, the structure model is repeated on the scale of building-to-grid, instead of DSO-to-TSO. Agreement is reached at the common point of connection on the exchanges and the grid do not need to have visibility into the interior state of the building. In return, individual devices in the building interact with the grid only via the BMS. This allows for a clean interface and clear roles and responsibilities, exactly as with the grid itself. Because the Laminar Coordination Framework yields multi-scale structures, the method works as well at the building level as at the grid level.

[22] B Nordman, Grid Architecture for Buildings, Lawrence Berkeley National Laboratory, December 2019.

In the forgoing paragraph, replace building with microgrid and the rest applies exactly. It is also feasible to continue the structural recursion and apply Laminar structure inside the building or microgrid.

Specification 5 details:

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

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

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

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

5.5 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 to Specification 1).

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

5.7 Use Laminar structure to define building-to-grid and microgrid-to-grid interfaces.

Specification 6: Logical Energy Networks and Distribution Virtualization

DER may be used to support grid resilience but present grid structure makes this difficult. Figures 1 and 2 show distribution systems organized by 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 BPS 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 requirement above)
- Volt/VAR regulation (local)
- Grid services resource management (local)
- Local outage managment

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 21 shows a distribution feeder with LEN virtual structure superimposed.

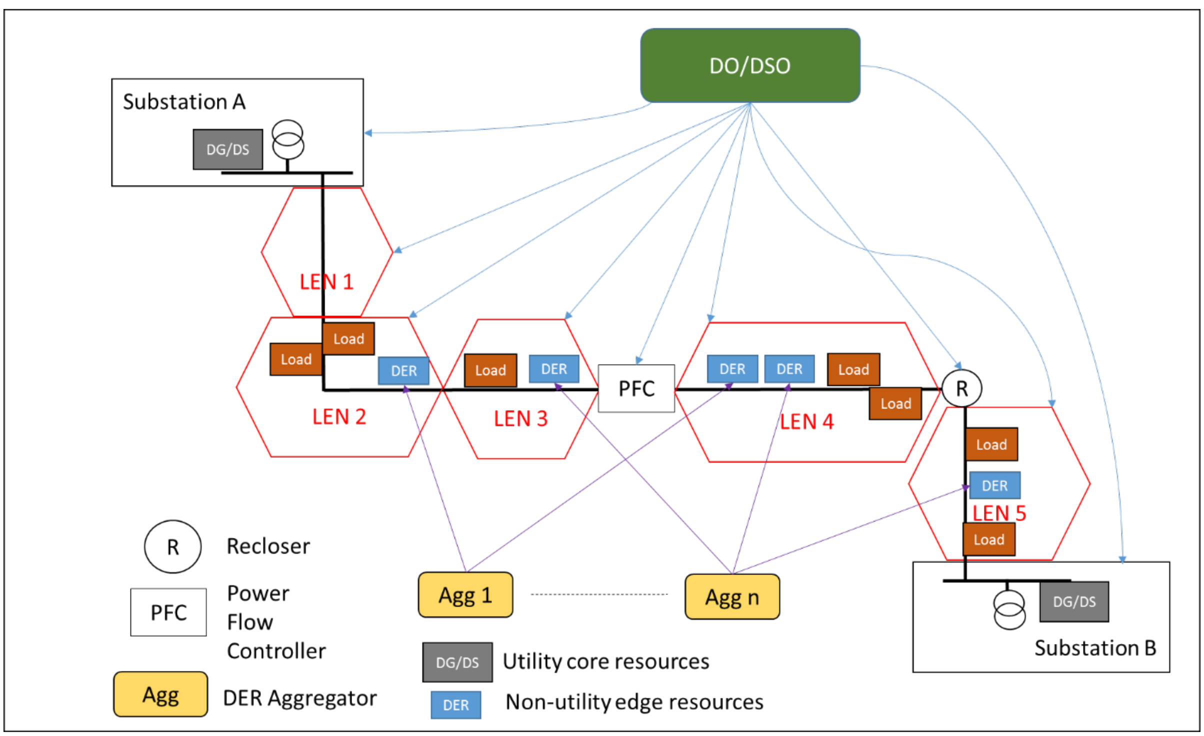


Figure 21 Example Feeder LEN Structure

This structure recognizes two classes of DER:

- Edge resources (non-utility owned and possibly not coordinated by a DSO)
- Core resources (utility owned/controlled by DSO)

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

- Power wheeling
- Interchange
- Inter-LEN outage support
- Inter-LEN Volt/VAR support

Given the LEN structure, Figure 22 shows the new stack model for the grid. Note the degree of parallelism between the structures of the BPS and the LEN-based distribution system. In order for the BPS to make use of the LENs, it must operate through the DSO, as indicated in Specification 1.

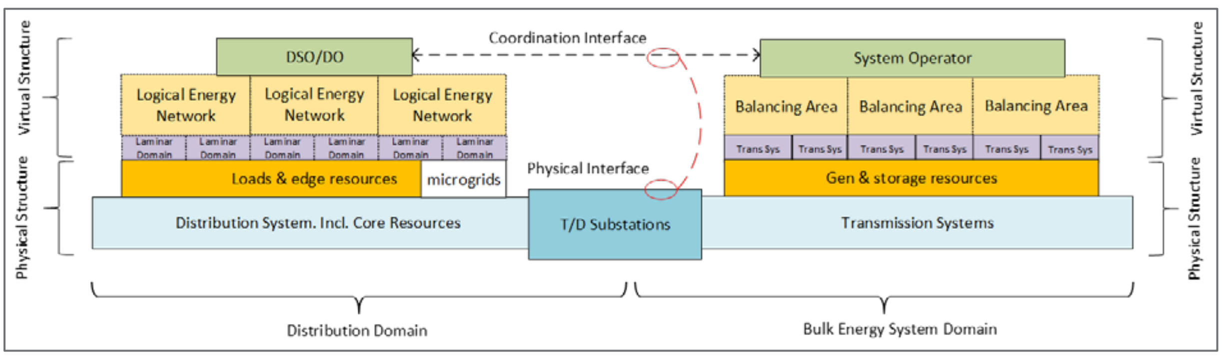


Figure 22 Grid Stack Model Diagram with LENs

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 BPS. For more information the concept of operation for LENs, see white paper *Logical Energy Network Concept of Operations*. 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.[23,24]

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

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

Operation Under Extreme Stress Conditions

Both Laminar Coordination and Logical Energy Networks can suffer disruption during extreme events such as severe storms, fires, etc. In such cases, electrical and communication infrastructure may be destroyed and so the overall structure may be fragmented, and resources may be isolated and unavailable at any given service point. In such cases, it is important that LENs or even fragments of LENs be able to continue operation to the extent possible given the infrastructure damage. For this reason, *distributed intelligence* is needed (as opposed to centralized, virtualized or cloud-based intelligence), with capabilities to determine what resources remain available on a local basis and to organize and operate those resources to meet local objectives. This may include cooperation with and support of neighboring LENs if such is possible, or it may mean operation in complete isolation.

While the platform model shown in Figure 22 is useful for isolating the underlying infrastructure from changes in the application level above, the reverse is also true. This is commonly seen with smart phones and with PCs, where the underlying hardware may change without any need to revise applications. An intermediate layer (the firmware layer called the BIOS[25] in the case of a PC) handles the changes in underlying hardware. In the grid case, the same principle applies. When the underlying hardware is changed (such as by a major disruption) the "application layer" of control can be insulated from the changes in the sense that it manages a set of available resources for a given circuit/load structure. In this case the Laminar Network plays the role of the BIOS, except that the Laminar Network must be capable of handling the underlying changes in a dynamic fashion. This has implications for the nature of the intelligence incorporated into the Laminar nodes (see Figure 18) and for circuit structure and use of power electronics (see Figure 9).

For systems using the communications/sensor layer model of Specification 3, local intelligence must be able to determine which communication paths and sensors remain available. In the case of microgrid islanding, if a portion of a distribution grid is included inside the island, a means is needed to let the local microgrid controller access the distribution grid communication network and sensors during the period of isolation, and then relinquish access after islanding is ended, with implications for communication network access control. Alternatively, the microgrid might have its own redundant sensing and communications, by arrangement with the distribution utility.

Other Distribution Structures

Other distribution level structures are also potentially useful for grid resilience purposes, such as agile/fractal grids, community microgrids, and microgrid networks. These are considered in the Variable Structure Grids Reference Architecture Package.

[25] Basic Input Output System

Specification 6 details:

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

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

6.3 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.

6.4 Each LEN has a local control/intelligence capability that supports local load and energy resource management, as well as operation under conditions of grid fragmentation.

6.5 LENS are coordination via Laminar Coordination and a DSO.

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

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

6.8 LENs supports neighbor LENs via power wheeling and interchange, outage support, and Volt/VAR support.

Specification 7: Fault Location, Isolation, and Service Restoration (FLISR)

FLISR is actually made up of several fault management steps:

- detection
- characterization
- location
- isolation
- service restoration (short term)
- service restoration (long term after fault correction)

A consideration of various approaches to fault detection, characterization and localization suggests the value of distributed intelligence.[26] Detection, characterization, and location are greatly aided by distributed sensing and analytics, so that the architectures of Specifications 3 and 8 apply. See also Specification 10, section 10.4.

Isolation and service restoration depend largely on circuit structure. With simple radials, very little can be accomplished besides simple sectionalization ahead of the fault. With increasing feeder meshing, more possibilities exist for re-routing of power flow. FLISR technology is well established, so the focus here is on aspects of circuit structure and grid virtualization. The amount of circuit interconnection (meshing) is subject to a variety of constraints and so is an engineering issue, specific to each grid situation.

The LEN model contains aspects useful for FLISR. 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. Figure 23 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 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, and then finally to two substations connected to two separate transmission systems.

[26] J Taft, Fault Intelligence: Distribution Grid Fault Detection and Classification, PNNL-27602, Sept 2017, available online: https://gridarchitecture.pnnl.gov/media/white-papers/FaultIntelligence_PNNL.pdf

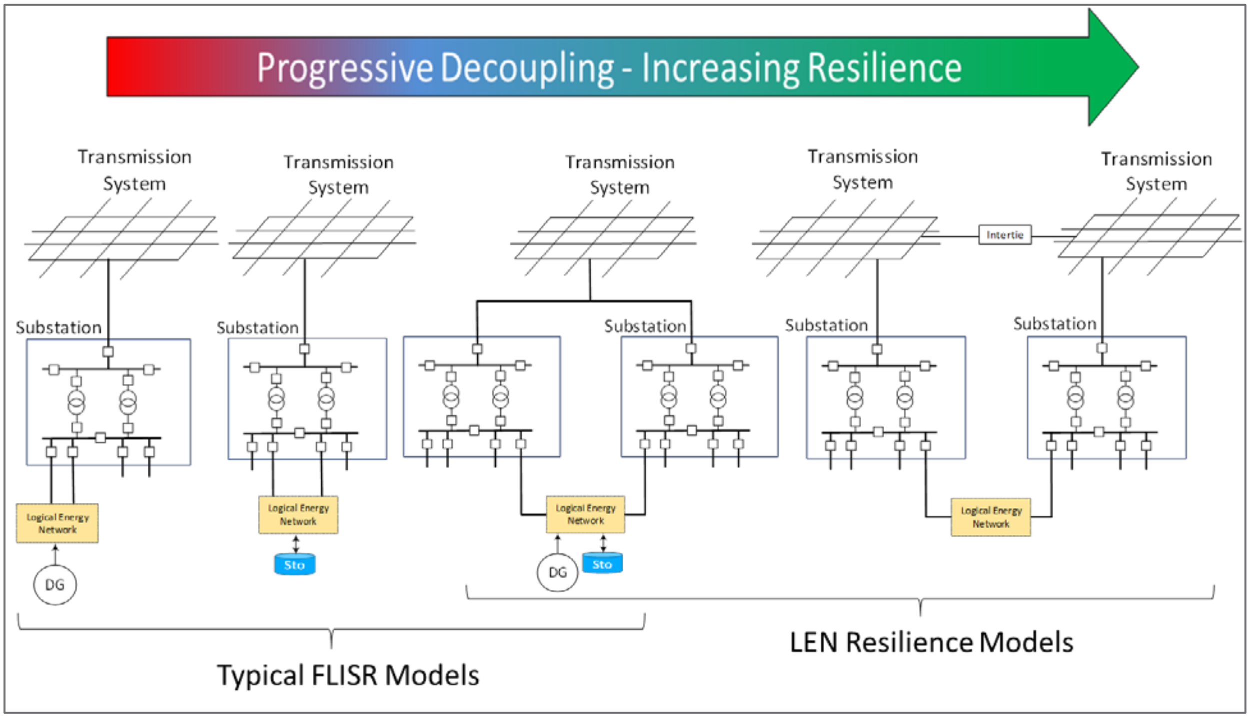


Figure 23 LEN Feeder Circuit Resilience Structures

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 7 details:

7.1 Use distributed sensing and intelligence architectures to support fault management.

7.2 Use circuit meshing as feasible to provide options for re-routing power around isolated faults.

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

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

7.5 Arrange for the two substations to be supplied from two different transmission systems, where feasible, or at least two separate transmission lines.

Specification 8: 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 computing hardware but three layers of firmware/software. Figure 24 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.

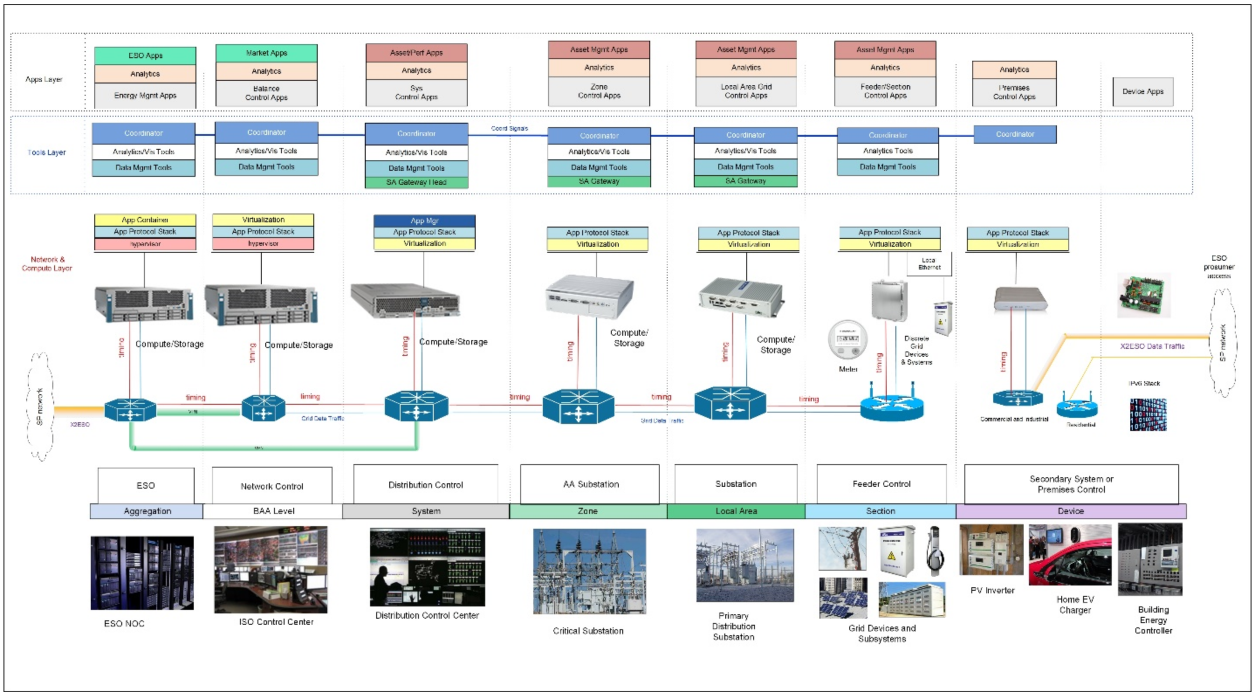


Figure 24 Electric Grid Distributed Intelligence Platform

Note that the use of Laminar Networks (Specification 5) 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,[27] 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.

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[27] 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 8 details:

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

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

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

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

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

8.5 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 9: Cyber Security Structures

A wide array of standard network security measures, devices and methods have been developed are in practice in many utilities. In practice, network level security should be viewed as a multi-layer, multi-measure framework based on four pillars:

- Access control
- Data integrity, privacy, and confidentiality
- Intrusion resistance, detection, and mitigation
- Device and platform integrity

Using these as basic principles, an extensive variety of technical measures may be applied at the communication network level. These are all available in product form and so can be applied at the design stage. An understanding of these is helpful to developing the architectural specifications that facilitate or require such measures.

The following is a list of standard network cyber security measures that any communication network operator should include as the minimum to be considered as part of a comprehensive cyber security program. It does not address people and process issues, but those are vital as well. Two processes to consider are manufacturing supply chain security management and secure code development and code hardening (against buffer overflow, self-modification; remove unnecessary protocols).

The technical measures list:

- Crypto: link layer, group, and application layer
  - GDOI as it has been incorporated into IEC 61850-90-5 specifically for PMU network encryption
- Role-based Access Control (RADIUS and TACACS; AAA; NAC)
- Mutual authentication; media-independent identity authentication protocols
- X.509, secure key generation and management, scalable key management (DMVPN, GETVPN for example)
- SIEM, firewalls
- Intrusion Prevention System (IPS), including SCADA IPS signatures
- Containment: Virtualization and Segmentation
  - VRF – virtual routing and forwarding
  - MPLS VPN and VLAN
  - data separation
- Tamper-resistant device design, digitally signed firmware images, firmware/patch authentication and integrity verification
- Digitally signed commands
- Rate limiting for DOS attacks
- Wire speed behavioral security enforcement
- Packet tamper detection, replay resistance
- SUDI 802.1AR (secure device identity)
- Access control: VLANs, ports
- Storm detection and traffic flow control: traffic policing and port blocking
- ARP inspection; DHCP snooping
- Honey pots/honey nets/sinkholes
- Unicast reverse path forwarding (IP address spoofing prevention)
- Hierarchical QoS
- Security policy managers
- MAC layer monitoring

- Control plane protection (coarse packet classification, VRF-aware control plane policing)
- Six wall physical security for devices and systems; access detection and mitigation (i.e. port shutdown)
- Anti-counterfeit measures
- Air gapping (physical network isolation, data diodes)
- Structure for securability

Some related security elements that are not network components or functions include:

- Secure code development and code hardening (against buffer overflow, self-modification; remove unnecessary protocols)
- Manufacturing supply chain security management
- Data quality as tamper detection
- Anti-counterfeit measures
- Security posture assessment

There are also a variety of people and process elements that must be included to secure power grids but are beyond the scope of this document.

In addition to these standard approaches, give consideration to the effect of structure on cyber vulnerability. Vulnerability is related to connectivity and the grid has two forms of connectivity: communication and electrical. Choice of structure to minimize attack avenues is a valid technique and, in this regard, Laminar structures provide better characteristics than hub-and-spoke arrangements that are common in SCADA and some DER management architectures.

Specification 9 details:

9.1 Systematically apply the network level security measures listed above

9.2 Consider the effect of structure and choose structures that inherently limit vulnerabilities by limited exposure of devise, systems and entities.

9.3 Consider the use of resilience as a cyber defense, instead of relying only on IT-type defenses.

Specification 10: Distribution Automation and Distributed Control

This reference architecture presumes high level of distribution automation, involving all aspects of distrbution control (power flow, Volt/VAR regulation, stabilization, synchronization, protection, and DER coordination). The specification focuses on structures, not algorithms.

10.1 Distribution Grid Control Structures with DER Coordination

The layered decomposition framework provides a common basis for developing distribution control architectures involving DER. Four specific examples follow to illustrate the commonality across applications.

Non-Utility Distributed Generation

Generators may be attached to distribution grids and may be owned by non-utility entities. Since their operation affects grid operations they must be coordinated and controlled in a beneficial manner that avoids creating reliability issues. Figure 25 shows how to apply laminar structure so that the utility, the generator devices, and any possible third parties can operate in a coordinated manner. Note that the cluster control layer may be implemented at the utillity or by DG operators (who may be separate from the DG owners). This structure mirrors the layered decomposition framework shown in Figure 17 in Specification 5.

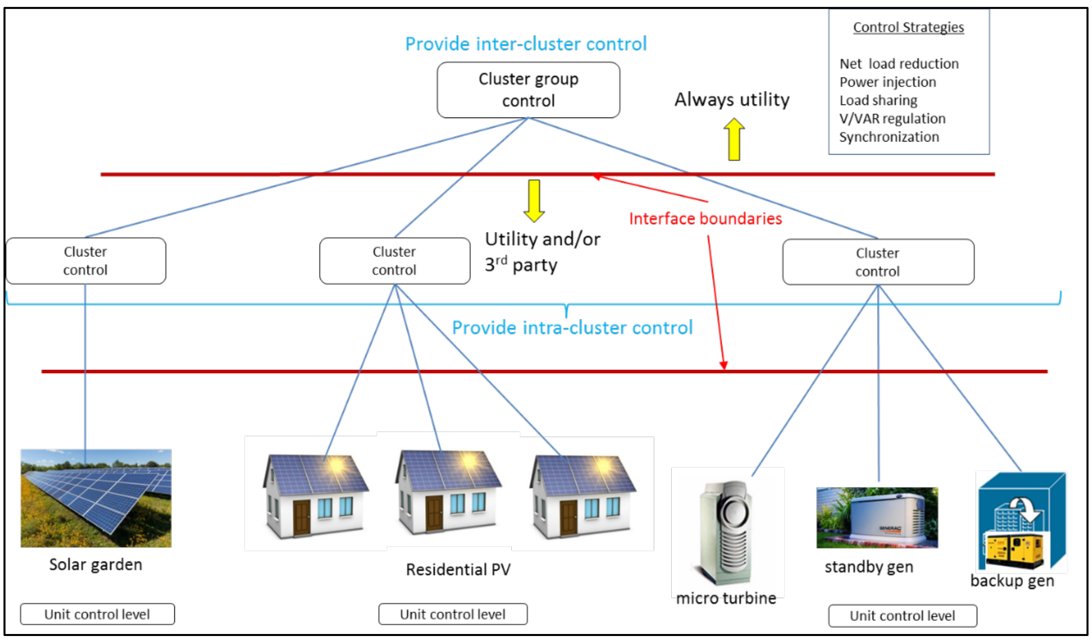

Figure 25 Laminar Coordination of Distributed Generation

Injection/Inverter Control

Many DER devices interface to the grid via power electronic inverters so they can inject energy into the grid. It has been propsed that such devices could not only provide the power injection interface, but also particpate in Volt/VAR regulation. If the control of such devices is purely autonomous on a per device basis, the potential for interference and reliability compromise exist. The problems can be avoided through use of a properly strctured coordination framework, as illustrated in Figure 26. Note the similarity to Figure 25. This framework also applies to grid-forming inverters,[28] even if the utility is not involved. In that case, the top level coordination node resides in the inverter network.

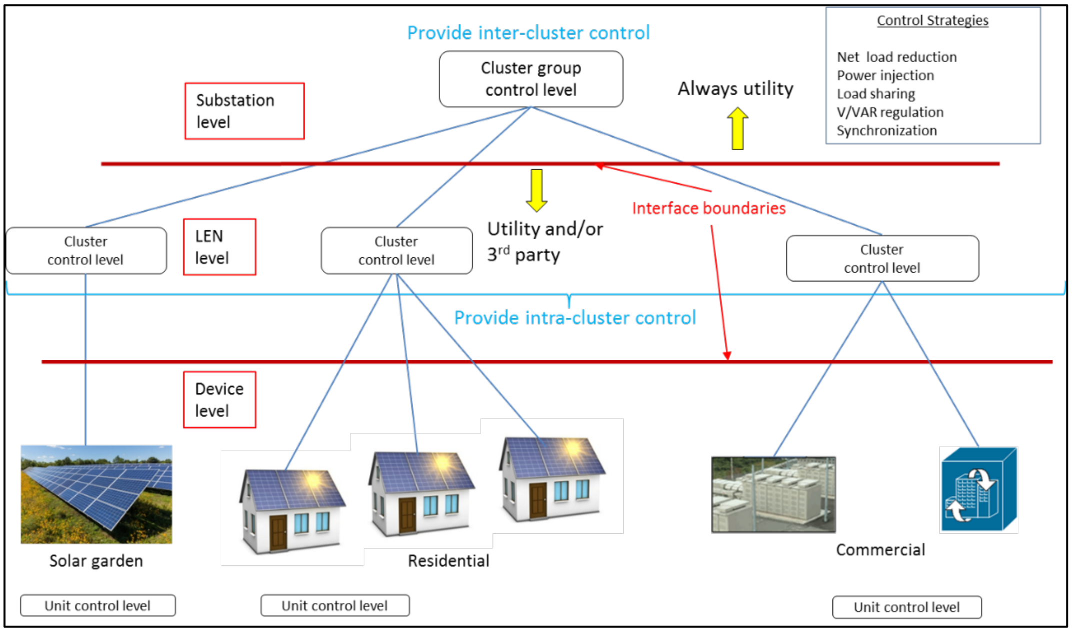

Figure 26 Laminar Coordination of Inverters

EV Charging Networks

EV charging newtoks represent a special case in that a potentially scare resource (charging capacity) may need to be allocated among vehicles (only true if insufficient charging capacity exists at the charging points). In this case, not only does the same framework structure apply, as shown in Figure 27, but the layered decomposition mathematics has been developed for the analogous case of allocating cell tower bandwidth to cell phones to provide implementations for the actual control strategies, using α-fairness[29] or power-constrained rate allocation.[30]

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[28] S Xue, Grid Forming Inverters, PowerPoint Presentation, ORNL, June 2019.
[29] M Chiang, et al., Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures, Proceedings of the IEEE, Vol. 95, No.1, Jan 2007.
[30] D Palomar and M Chiang, Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications, IEEE Transactions on Automatic Control, Vol. 52, No. 12, December 2007.

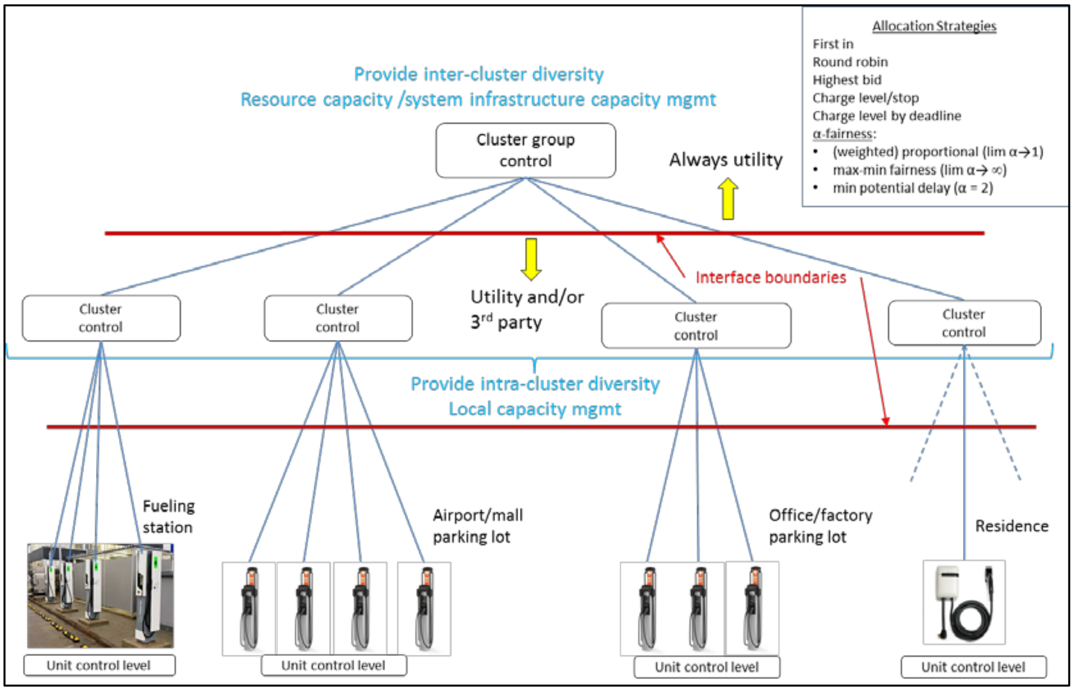

Figure 27 Laminar Control of EV Charging Networks

Note that the same basic methods also provide solutions for optimal scheduling, routing, and congestion control, which could be applied to distribution network operations in the context of using the distrbution systems as an energy transaction platform. In other words, the control of flow control and Volt/VAR regulation devices could be managed by the utility using similar methods and structure.

<u>Hetergeneous DER Networks</u>

When DER develops "organically" (meaning not planned by the electric utility), the utility may be faced with coordinating mixed sets of resources the vary from place to place and from time to time. The use of the LEN concept is helpful because it privdes a means to virtualize the distribution physical layer so that management methods above the LEN layer do not have to shift constantly to accommodate changes in underlying physical DER. Figure 28 shows how this mapping fits into the same strctural framework as the other examples above.

Using the Laminar network methods, third party operators of DER can be accomodated. However, note that when Net Energy Metering tariffs are eliminated, it is not necessarily the case that the utility must work through intermediaries. An emerging mode for DER control is for the utility to provide a tariff payment that is essentially for use of the DER in a capacity mode; that is, there are no stacked values and no real time market-like mechanisms. Instead the owner agrees to allow the utility to operate the DER in any mode it wants (within limits that protect the owner) and for any operational purpose that utility may have at any specific time, for which the owner receives a simple payment.

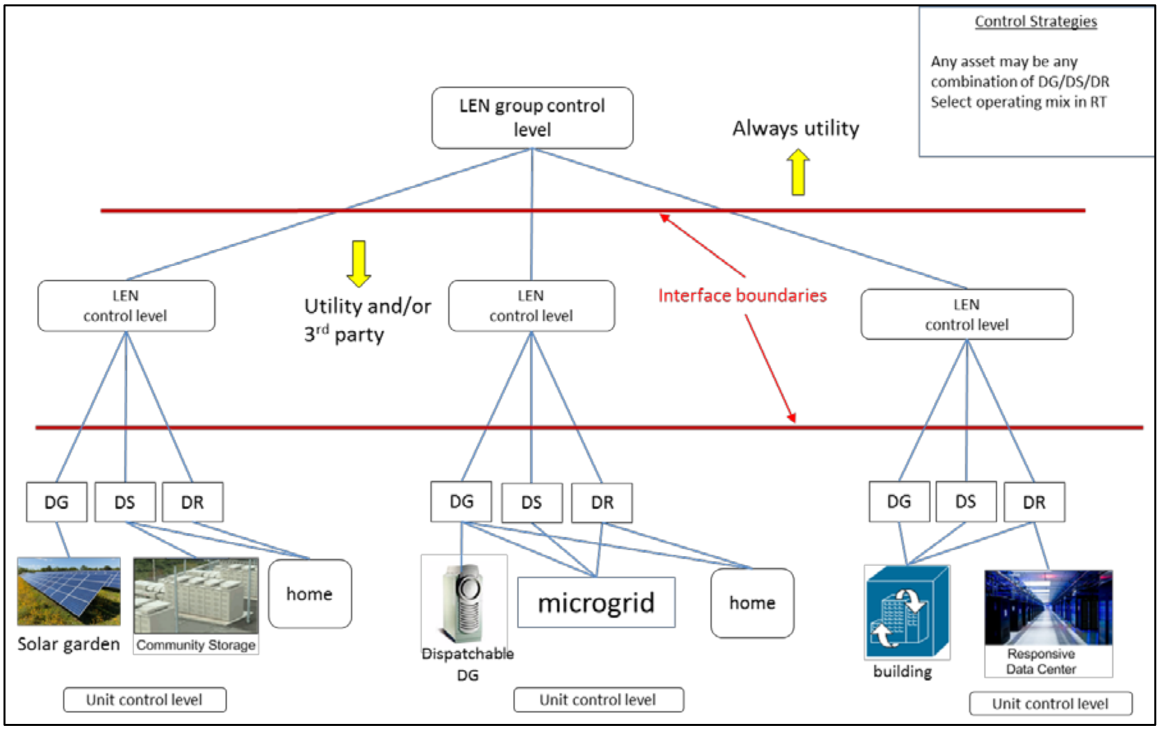

Figure 28 Layered Control of Heterogeneous DER Networks

10.2 Feeder Control

Control structure addresses power system control in the presence of large numbers of customer, utility, or third-party owned distribution connected assets (DER) and utility distribution automation. This structure supports a combination of centralized, decentralized, and distributed control mechanisms. The support for a range of mechanisms recognizes that for some time many distribution systems will have varying penetrations of DER thus requiring multiple control approaches. The control structure considers scalability and evolution of control strategy with growing DER penetration. The control objectives considered include regulation of voltage, reactive power and frequency, stability, power flow including congestion management, and synchronization.

The control and coordination structure must accommodate DER penetration at varying levels and within both radial and meshed feeder topologies. It must also be robust against structural variability in system topology that occurs through the operation of distribution automation devices such as automated reclosers. This is illustrated in Figure 29 which is based on an urban meshed network portion of a large distribution system. In the figure note that behind the meter DER may distributed on any segment and that there are possibilities for microgrids attached through a recloser to any given segment and utility scale DER as well, in this case directly at the substation. Considering this example and generalizing several structural considerations for control and coordination with distributed automation are apparent. Accommodating the range of possible operational configurations requires that the structure start with control and coordination of each individual segment.

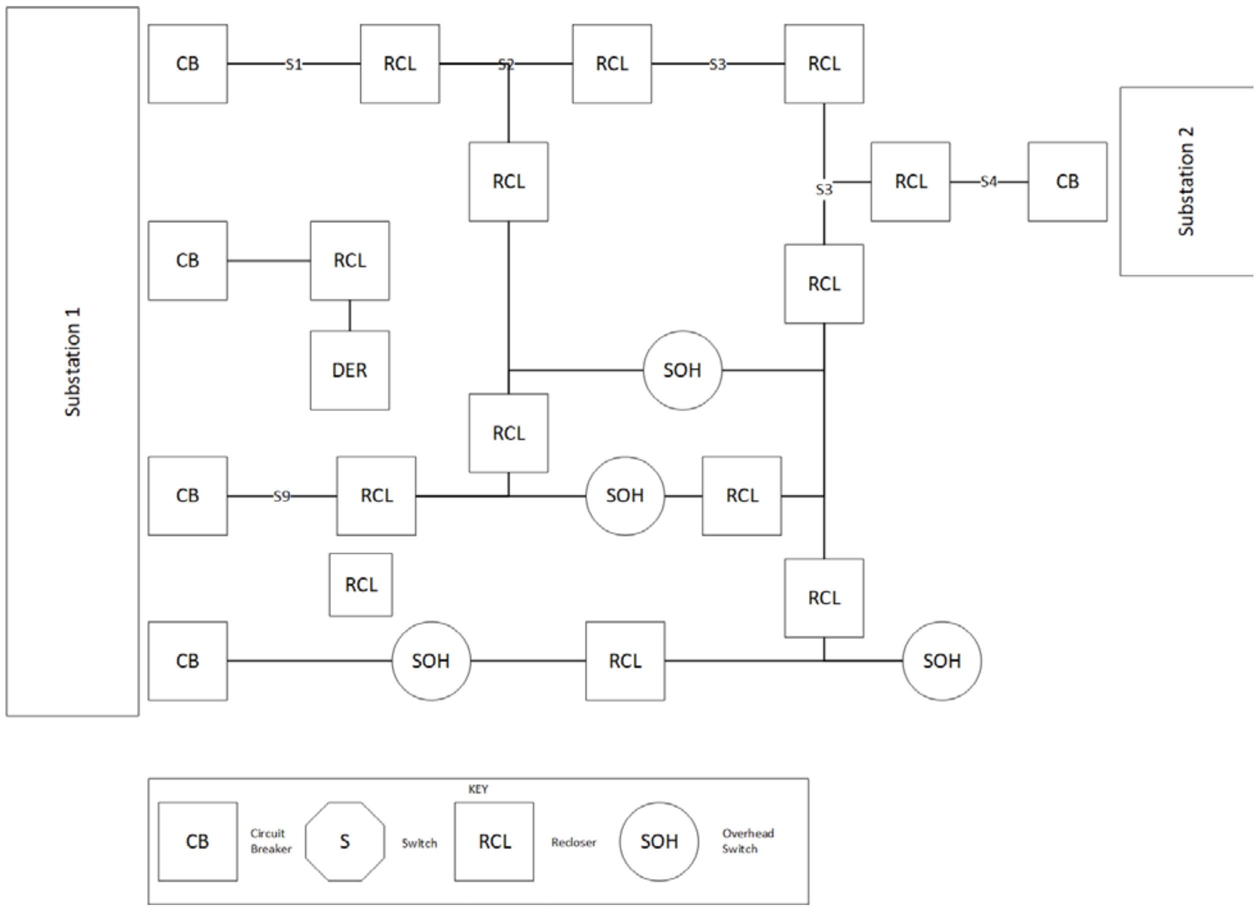

Figure 29 Hypothetical meshed distribution feeder with high DA

<u>Basic Structural Considerations</u>

Starting with the segments, a layered approach provides a uniform logical structure that may apply to all the possible physical configurations. For each segment, the DER interconnect in such a manner that the lowest layer of control and coordination balances power flow within the segment, meeting power flow and voltage constraints (objectives) at the segment ends. Constraints may also from the next layer above that is coordinating across some collection of segments. This layer and the DER or distribution automation devices (protection, switchgear, and power flow control) accommodate autonomous responses, allowing devices to adjust net load to support regulation of voltage or frequency based on measurements at their location. Figure 30 illustrates the basic control structure in the context of an entire regional grid.

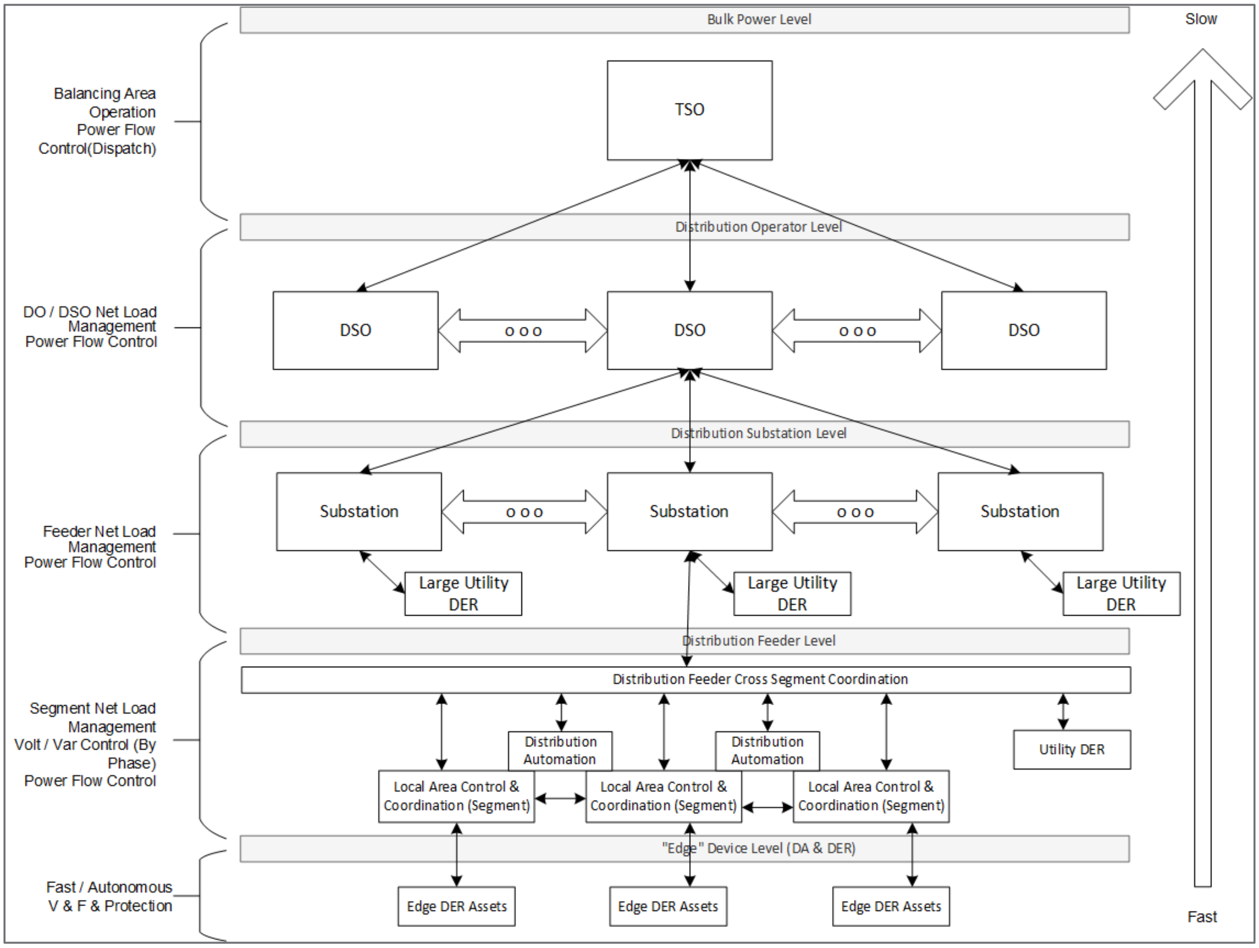

Figure 30 Basic layered, logical structure for control and coordination of high DA / DER Feeders

In Figure 30, each layer has an interface between logical and physical and “local” coordination of DER behavior through information sharing between the DER located on that segment and in the context of constraints and objectives passed to that layer can be performed. Through local coordination, optimize voltage on that segment and coordinate power flow at the connection points to adjacent segments via objectives and constraints shared at the next level up in a manner consistent with a laminar coordination framework layered problem decomposition.

Figure 31 puts the lower layers of structure from Figure 30 into the context of logical energy networks (LENs.) LEN is a logical construct associated with each segment (see Specification 6). The LEN provides a common structural element with a uniform interface to the layer(s) above. The LEN must be matched to the physical infrastructure of the segment with a combination of communications, sensing, and actuation interfaces for each device. Finally, note that this structure is consistent with the different control and coordination operational time scales from fast acting edge devices, for example automated reclosers, to processes that deal with progressively slower time scales as one moves away from the grid edge.

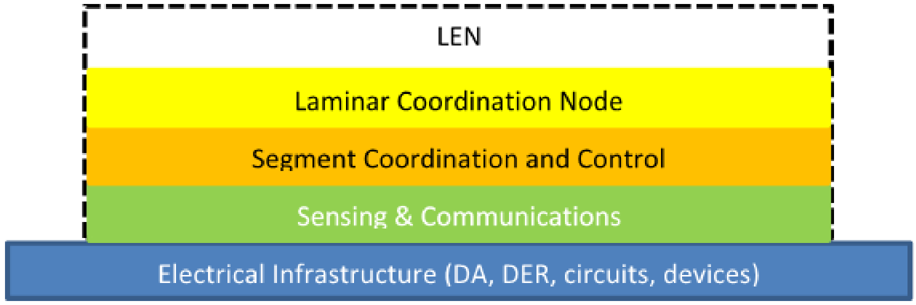

Figure 31 LEN view of lower layer of laminar coordination

The alignment with the logical energy network structure also puts the hierarchical structure with local segment coordination into alignment and relationship with the sensor communication structure (Figure 11), the laminar coordination domain structure (Figure 1), and the grid stack model.

10.2 Specification details:

10.2.1 Compose distribution system topology from Distribution feeder segments as the basic structure building blocks.

10.2.2 Use structure for coordination and control that is consistent with Laminar Coordination Framework and LENs.

10.2.3 Plan for faster action near the edge, i.e., at the segment level, with time frame of action slowing as one moves upward the structure.

10.2.4 Accommodate DER at any level in the structure.

10.2.5 Provide support for segmentation of the control to handle normal failures in communications, coordination, and control, including fallback isolated operation when necessary.

10.3 Electrification of Transportation

The growth of electrified transportation carries with it several potential systemic issues that may be dealt with using grid architectural principles. Recent studies analyzing state and national-level electric vehicle infrastructure needs have estimated that substantial deployments of new Electric Vehicle Supply Equipment (EVSE, also known as charging stations) are required to meet near-term emissions goals and to support the robust use of millions of Plug-in Electric Vehicles (PEV)[31,32]. Large deployments of PEVs and commensurate EVSE – for example, Direct Current Fast Charging (DCFC) stations, which can supply tens to hundreds of kilowatts[33] – lead to grid issues related to power quality and equipment lifetime. Additionally, while pilot studies of V2G and V2B systems have demonstrated that vehicle fleets can support ancillary services and demand response, such experiments have faced significant resource aggregation, logistics, control, and market integration challenges.[34]

Along with the many challenges, electrified transportation may also enable the integration of intermittent energy sources such as wind and solar[35]. Conceptually, aggregations of PEVs may act as buffers that smooth the output of intermittent generation (see Specification 4).

Laminar Decomposition of Electric Vehicle Charging Infrastructure

Unstructured expansion of EVSE infrastructure may ultimately result in a vast, heterogeneous collection of charging stations with diversity of supply capability, ownership, communication capability, and spatial location and density. A structured, layered approach can be used to support load diversity, aggregation, and appropriate coordination and control of these resources. Figure 32 describes the application of conventional laminar decomposition to charging infrastructure.

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[31] Wood, E. W., Rames, C. L., Muratori, M., Srinivasa Raghavan, S., & Melaina, M. W. (2017). National plug-in electric vehicle infrastructure analysis (No. NREL/TP-5400-69031; DOE/GO-102017-5040). National Renewable Energy Laboratory, Golden, CO (United States), available online: https://www.nrel.gov/docs/fy17osti/69031.pdf

[32] Bedir, Abdulkadir, Noel Crisostomo, Jennifer Allen, Eric Wood, and Clément Rames. 2018. California Plug-In Electric Vehicle Infrastructure Projections: 2017-2025. California Energy Commission. Publication Number: CEC-600-2018-001, available online: https://www.nrel.gov/docs/fy18osti/70893.pdf

[33] D Zhao and T Hong, EV Charging Station Trend.pptx, Argonne National Laboratory, May 2019.

[34] D Black, et al., Lawrence Berkeley National Laboratory. 2017. Los Angeles Air Force Base Vehicle-to-Grid Demonstration. California Energy Commission. Publication Number: CEC-500-2018- 025., available online: https://ww2.energy.ca.gov/2018publications/CEC-500-2018-025/CEC-500-2018-025.pdf

[35] T Markel, et al., Multi-Lab EV Smart Grid Integration Requirements Study. Providing Guidance on Technology Development and Demonstration (No. NREL/TP-5400-63963, 2015). National Renewable Energy Lab.(NREL), Golden, CO (United States), available online: https://www.nrel.gov/docs/fy15osti/63963.pdf

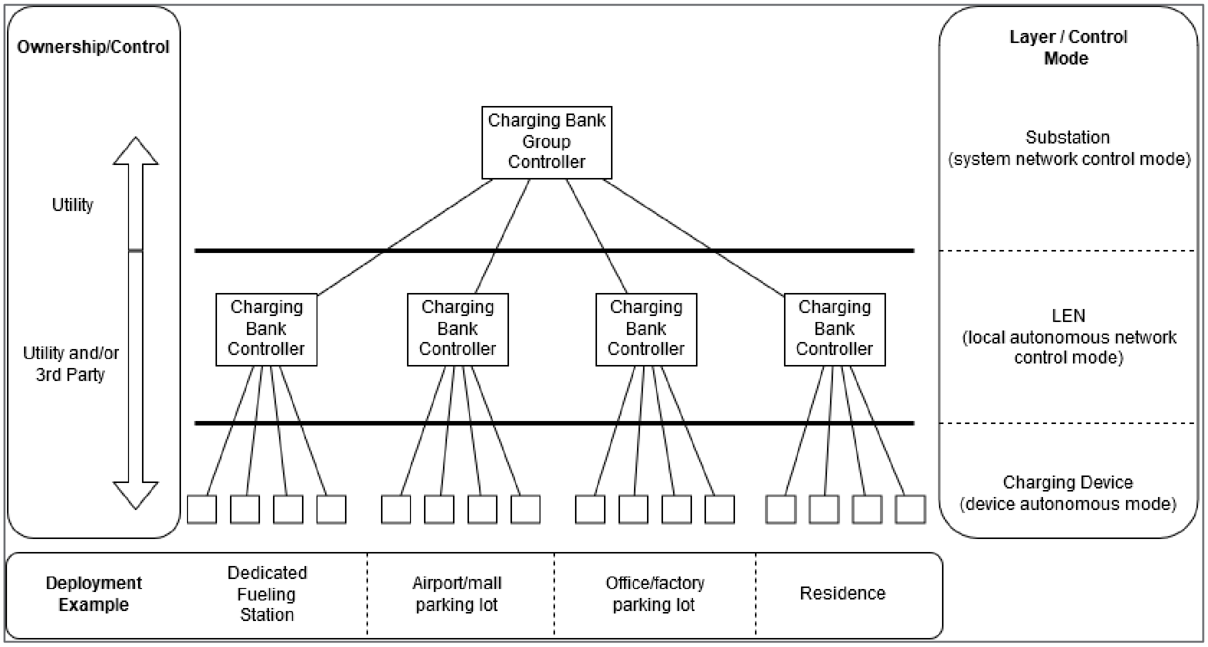

Figure 32 Laminar decomposition of stationary charging infrastructure for PEVs

Charging infrastructure is decomposed into three hierarchical layers: charging bank group controllers, charging bank controllers, and individual charging stations. Each layer corresponds to a specific ownership and control mode model. This type of structure can support load diversity, aggregation, and coordination/control in the face of unstructured deployment of heterogeneous PEV charging infrastructure.

By superimposing a layered structure onto charging stations, logical aggregations of stations and hierarchical associations of such aggregations can be formed. These aggregations, which may be dynamic in nature, map naturally to Logical Energy Networks (LENs). This mapping suggests that, at the least, charging station infrastructure can actively participate in general resilience-enhancing functions of a LEN.

With the appropriate communication structures, and an adequate population of charging stations, this layered approach may also enable the coordination of a diverse set of EV resources. The concept of α-fair resource allocation, described by Altman, et al.[36] and originally applied to sharing of wireless network resources such as throughput and SNR, may be adapted to this domain to enable fairness in allocation of charging stations and their supply capacity; by adjusting the value of α, different allocation

[36] E. Altman, K. Avrachenkov and A. Garnaev, "Generalized α-fair resource allocation in wireless networks," 2008 47th IEEE Conference on Decision and Control, Cancun, 2008, pp. 2414-2419, available online: https://ieeexplore.ieee.org/document/4738709

strategies may be implemented. Similarly, concepts from hierarchical batch job scheduling systems for high-performance computing (HPC) clusters[37] may be adapted to support charging resource allocation requirements. The core issue is that the coordination framework structure should be able to support any of these approaches and others.

Intelligent and Dynamic Aggregation of Electric Vehicles

Recent work on multi-objective optimization algorithms for charging of autonomous vehicles in demand-response environments take into account existing transportation infrastructure and driving patterns.[38] While the practical application of these technologies is highly dependent on large infrastructure investments, intelligent and dynamic aggregation of autonomous electric vehicles has the potential to address electric grid needs such as response to small-scale blackouts, avoiding renewable energy curtailment, and provisioning of ancillary services to the grid.

Figure 33 describes the formation of LENs to use EVs for mitigation of renewable energy source curtailment. In this example, collections of EVs associate with LENs as dynamically marshaled (in time and space) DERs.

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[37] H. Hussain, et al. 2013. A survey on resource allocation in high performance distributed computing systems. Parallel Comput. 39, 11 (November 2013), pp. 709-736, available online: https://www.sciencedirect.com/science/article/pii/S016781911300121X

[38] Iacobucci, R., McLellan, B., & Tezuka, T. (2019). Optimization of shared autonomous electric vehicles operations with charge scheduling and vehicle-to-grid. Transportation Research Part C: Emerging Technologies, 100, 34-52, available online: https://www.sciencedirect.com/science/article/pii/S0968090X18309197

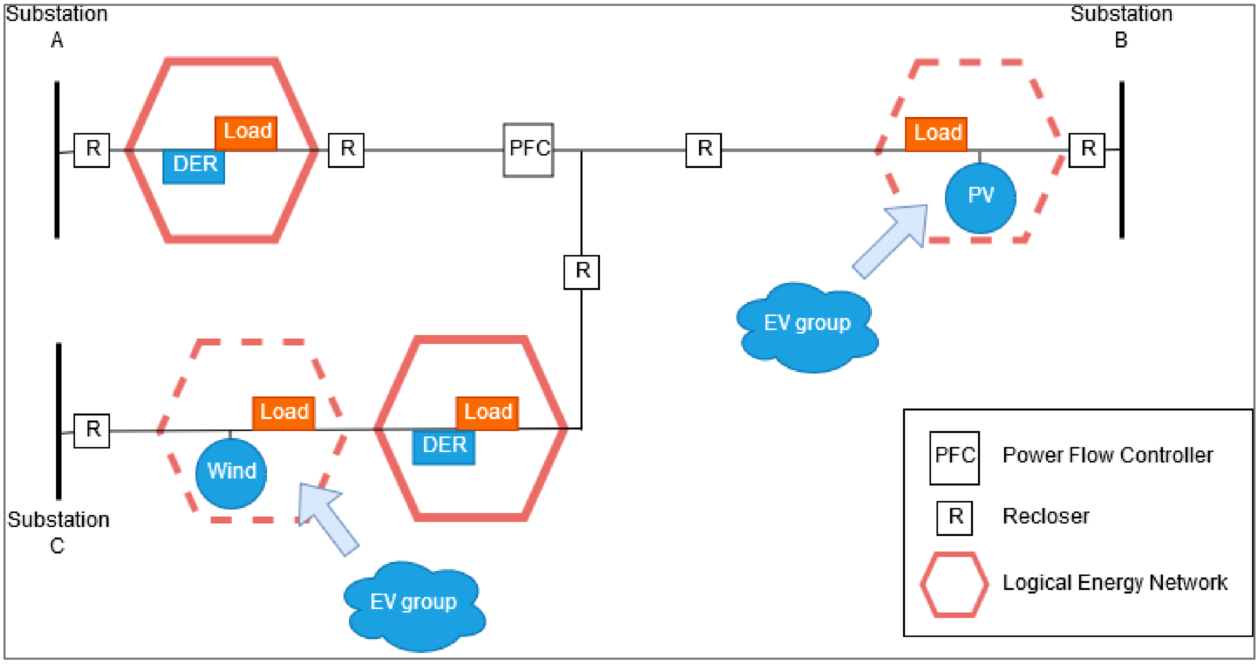

Figure 33 Autonomous electric vehicle dynamic groups joining/forming LENs to mitigate wind and PV curtailment

This model is not specific to groups of EVs; it may also be applied to electrified transportation that is less autonomous or less mobile. For instance, corporate vehicle fleets, mobile charging apparatus, and private collections of EVs may participate in this model. Furthermore, this model is not limited to curtailment or smoothing of renewable energy resources; it may also be applied to provision grid services such as load shifting, or to supply power during small localized blackouts. Figure 34 outlines a layered decomposition of multiple domains that expresses both the aggregation of resources that span technology types, and the inter-relationships between layers. Some applications may require integration with a DO/DSO, which is not shown in Figure 32.

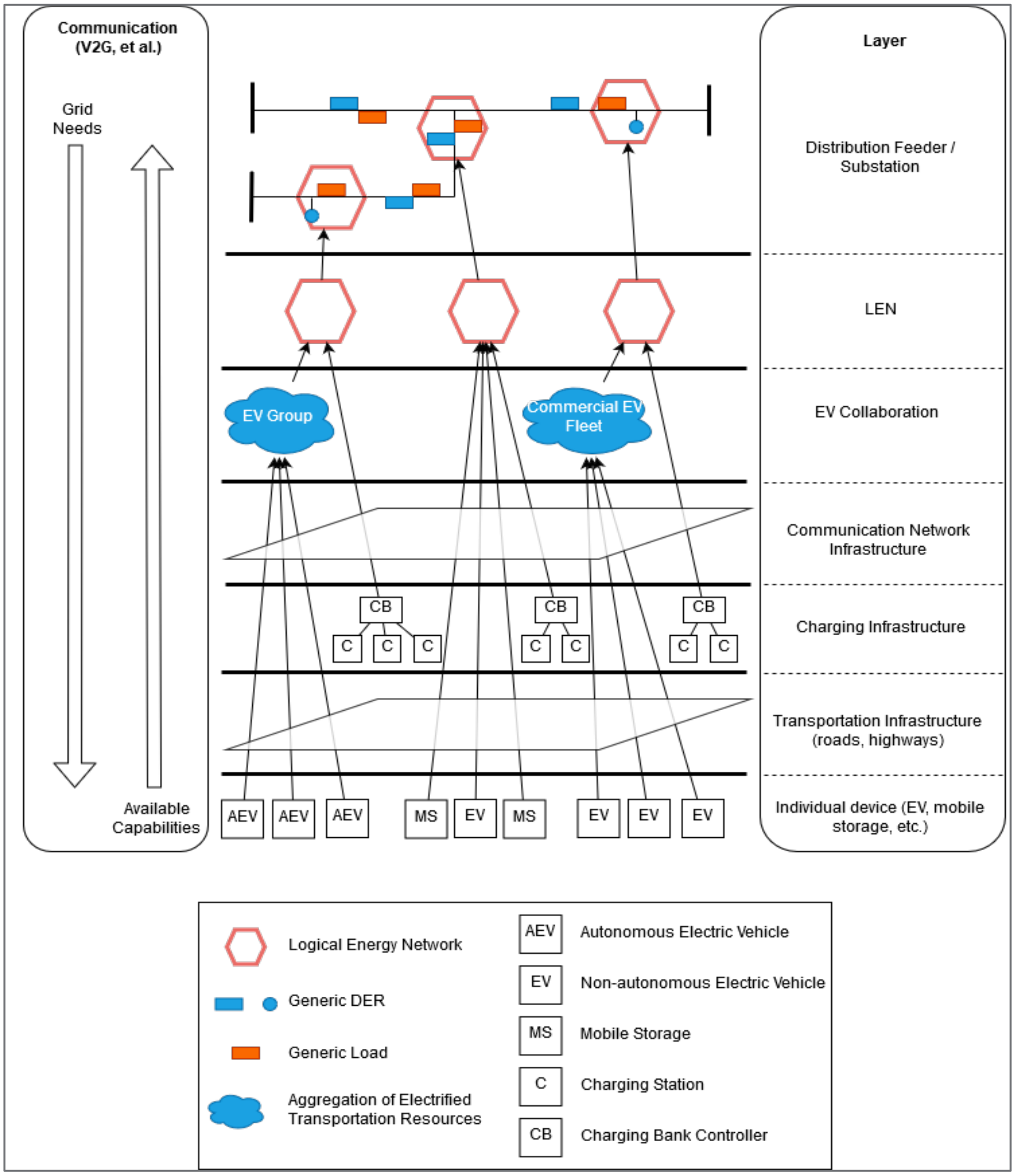

Figure 34 Layered decomposition applied to the synthesis of LENs and aggregated EV resources across multiple domains

Electrified Roadways, Electric Vehicles, and Ubiquitous Storage

Wireless or cellular communication is critical to the architecture of Figure 34: cellular radio base-station hand-off algorithms may be useful for managing the association of dynamic aggregations of mobile storage resources with specific areas of grid control as the resources migrate across a grid. Since electrified roadways would be effectively acting as feeders in this case, electrical connectivity to the conventional grid would need to be managed appropriately with segmentation of the electrical infrastructure comprising the electrified roadways – this would help to address the occurrence of faults in roadway "feeders." An overview of projects and technologies relevant to this concept may be found in the literature.[39]

Specification 10.3 details:

10.3.1 Use Laminar structure for organizing EV charging.

10.3.2 Use the LEN virtualization model to accommodate dynamic association of mobile assets in the case of electrified roadways.

10.4 Sensing and Intelligence in Distribution Grids

Sensing and intelligence for control and fault handling (protection) at the distribution level makes use of sensor networks and distributed intelligence for grid state determination and fault analysis (detection, characterization, localization, and prediction). Sensors may be used individually or in dynamic groups via the sensor/communication layer observability platform (see Specification 3), with processing intelligence located in the distributed intelligence platform (see Specification 8). The combination of these layers allows intelligence to be located as needed throughout the distribution grid, meaning that it can reside in the control center, in substations, or in individual LENs. Analytics and control applications may be centralized or distributed in nature. Hosting of applications may coincide with hosting of Laminar coordination nodes as per Figure 19 in Specification 5 or may reside elsewhere in the distributed intelligence platform.

[39] T Markel, et al., Multi-Lab EV Smart Grid Integration Requirements Study. Providing Guidance on Technology Development and Demonstration (No. NREL/TP-5400-63963, 2015). National Renewable Energy Lab, (NREL), Golden, CO (United States), available online: https://www.nrel.gov/docs/fy15osti/63963.pdf

FLISR actually consists of three stages: detection/characterization/localization, isolation, and service restoration. The last two are contreol functions and so make use of the pweor flow aspects of the control strcture described above. The first stage is a combination of sensing, communcations, and analytics. A large number of techniques are available for carrying out these steps, including the use of distribution level synchrophasors.[40] Since any particular grid observability strategy may use one or more of these methods and it may not be possible to know in advance which will be used (they may change over time), the structures support general sensor types, data flows, and processing structure models.

10.4 Specification details:

10.4.1 Sensing for distribution grid protection and control uses the observability platform structure and either the distributed intelligence platform structure or the Laminar coordination domain structure.

10.4.2 Sensors may be shared across multiple protection and control applications.

10.4.3 Direct sensor-to-local application data flows are permitted to provide low latency. Sensor data does not have to flow to a remote data store or broker first.

Specification 11: Communication 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 be concerned with network-based timing distribution.

11.1 Wide Area Network (WAN) structure for private networks is a multi-aggregation ring topology with linear aggregation strings. Figure 35 illustrates the basic form. This structure can be scaled as needed and can be implemented in a proportionally manner, so that incremental build-out is possible.

[40] J Taft, Fault Intelligence: Distribution Grid Fault Detection and Classification, PNNL-27602, September 2017. Available online: https://gridarchitecture.pnnl.gov/media/white-papers/FaultIntelligence_PNNL.pdf

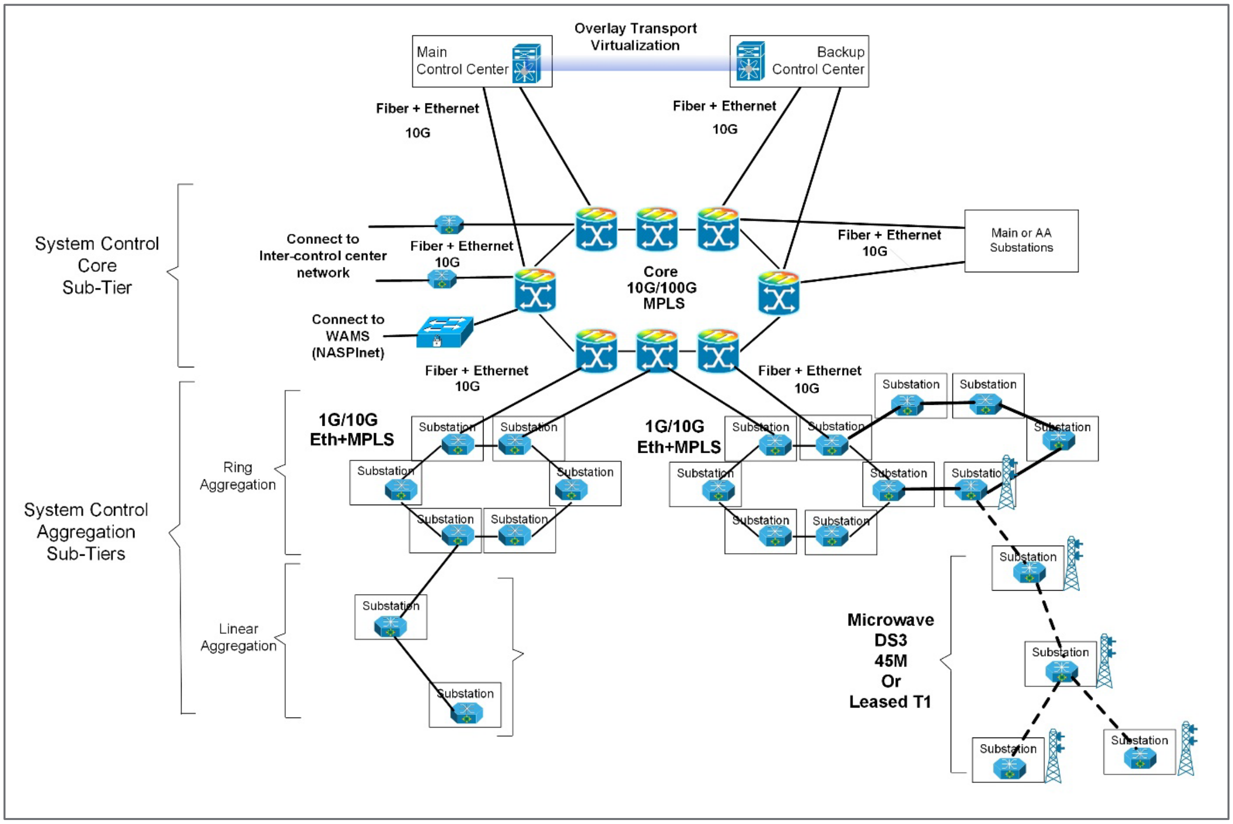

Figure 35 WAN Structure Diagram

11.1 Specification details:

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

11.1.2 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.

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

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

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

11.2 Substation networks for critical infrastructure in a high resilience architecture use the redundant tree topology of Figure 36. A variety of network topologies are available for substations and less critical substations may use less resilient approaches.[41] 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).[42] The cited document also provides topology comparisons and comparison of IEC 61850 over Ethernet vs. IEC 61805 over UDP/TCP over IPv4/v6.

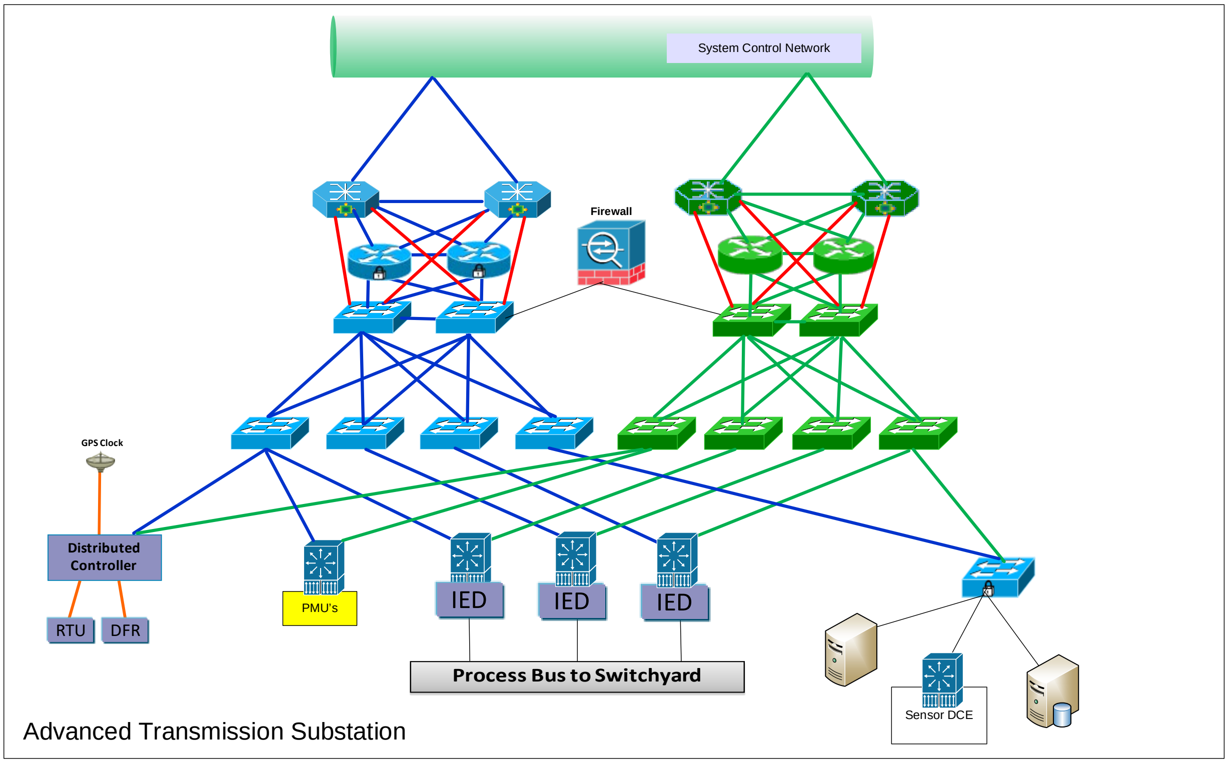

Figure 36 High Resilience Substation Communication Network

[41] 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.
[42] N. Yadav and E. Kapadia, Substation of the Future: Improve Network Reliability and Protocol Interaction, Grid Interop, December 2010, available online: https://www.gridwiseac.org/pdfs/forum_papers10/kapadiapre_gi10.pdf

11.2 Specification details:

11.2.1 Use meshed two-tier dual tree network topology.

11.2.2 Provide dual connections to the WAN(s).

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

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

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

11.3 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 37 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.

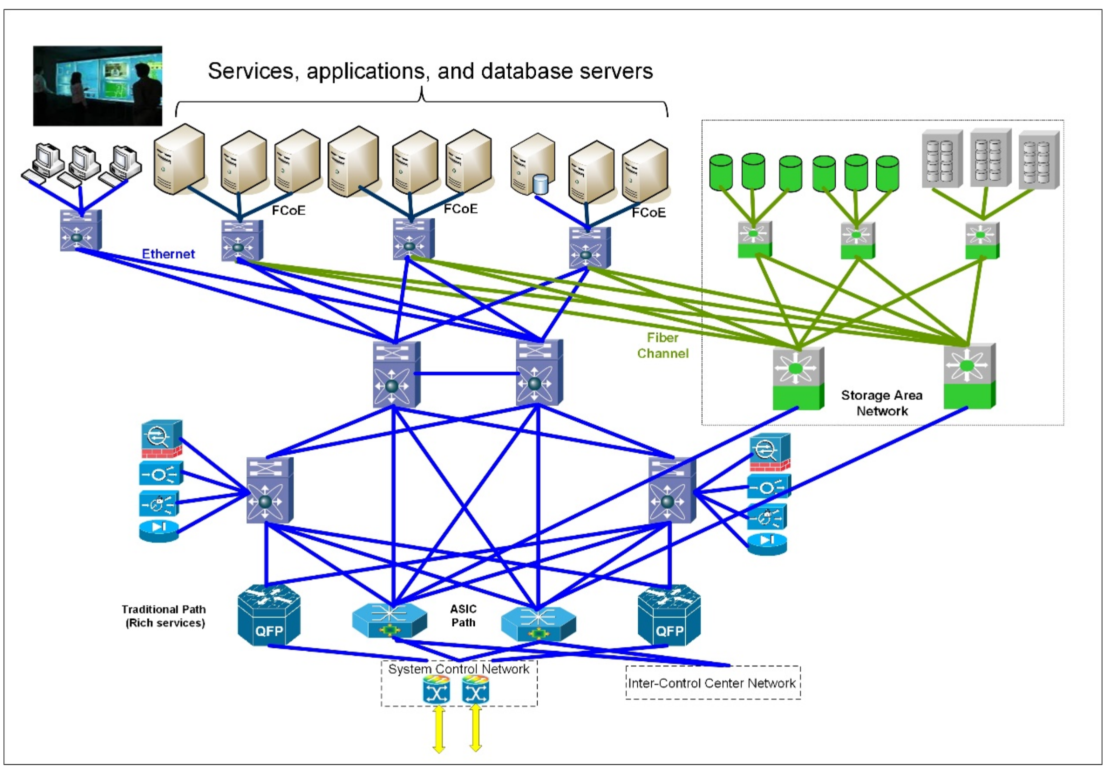

Figure 37 High Resilience Control Center Communications Network

When telecommunications service providers are used for wide area communications, the dual service provider model with redundant paths as shown in Figure 38 avoids the single point of failure problem (in this case outage of a service provider). Note the dual redundant connections on each end.

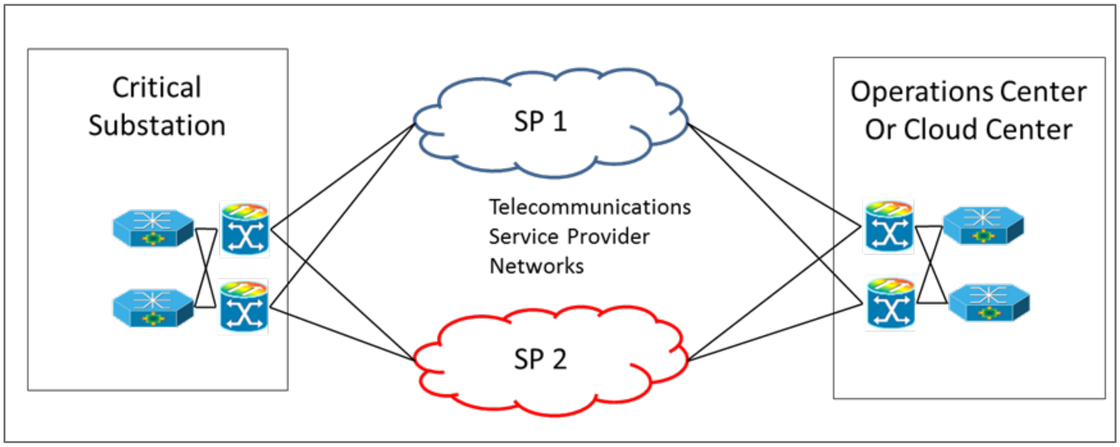

Figure 38 Redundant Telecommunications Service Provider Communications Structure

11.3 Specification details:

11.3.1 Use mesh multi-path topology.

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

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

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

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

11.4 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.[43] Consequently, additional sources and methods of synchronization are desirable in line with the NASPInet 2.0 architecture principles.[44] In Figure 39, 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.[45]

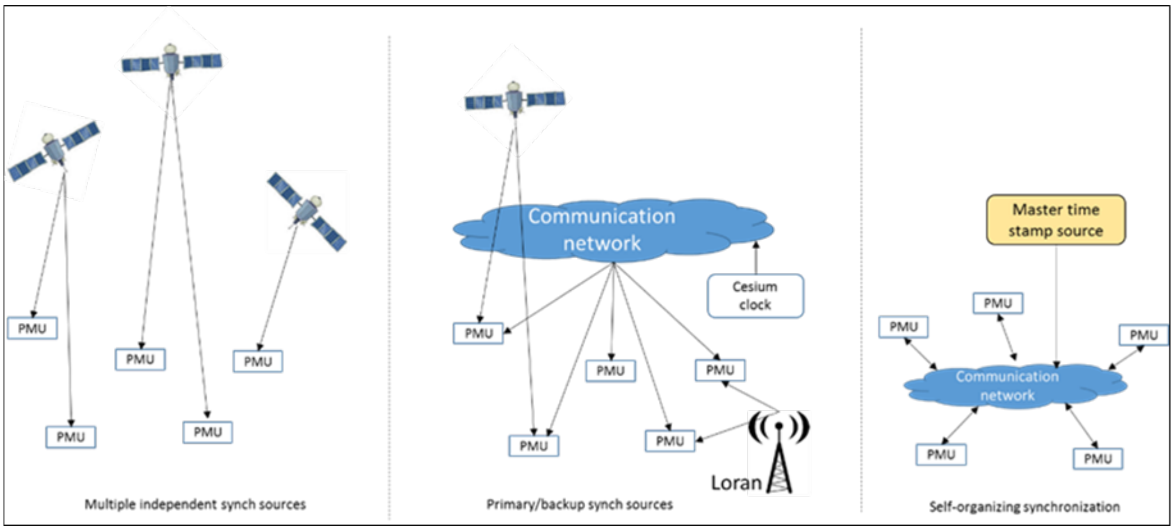

Figure 39 Network Timing Sources

Alternatively, a sensor network such as a PMU network may be self-synchronizing[46] 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, rather than at each sampling point. Such an arrangement requires that the measurement and control devices to be synchronized be able to

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[43] 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

[44] 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

[45] J Taft, NASPInet 2.0 Architecture Guidance Version 1.19, PNNL-28656, Sept. 2019, available online: https://gridarchitecture.pnnl.gov/media/NASPInet%202%20v1.19_PNNL.pdf

[46] 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.

communicate with each other, including across organization boundaries in the case of transmission-level PMU networks. Figure 40 illustrates a multi-organization network architecture for timing distribution.

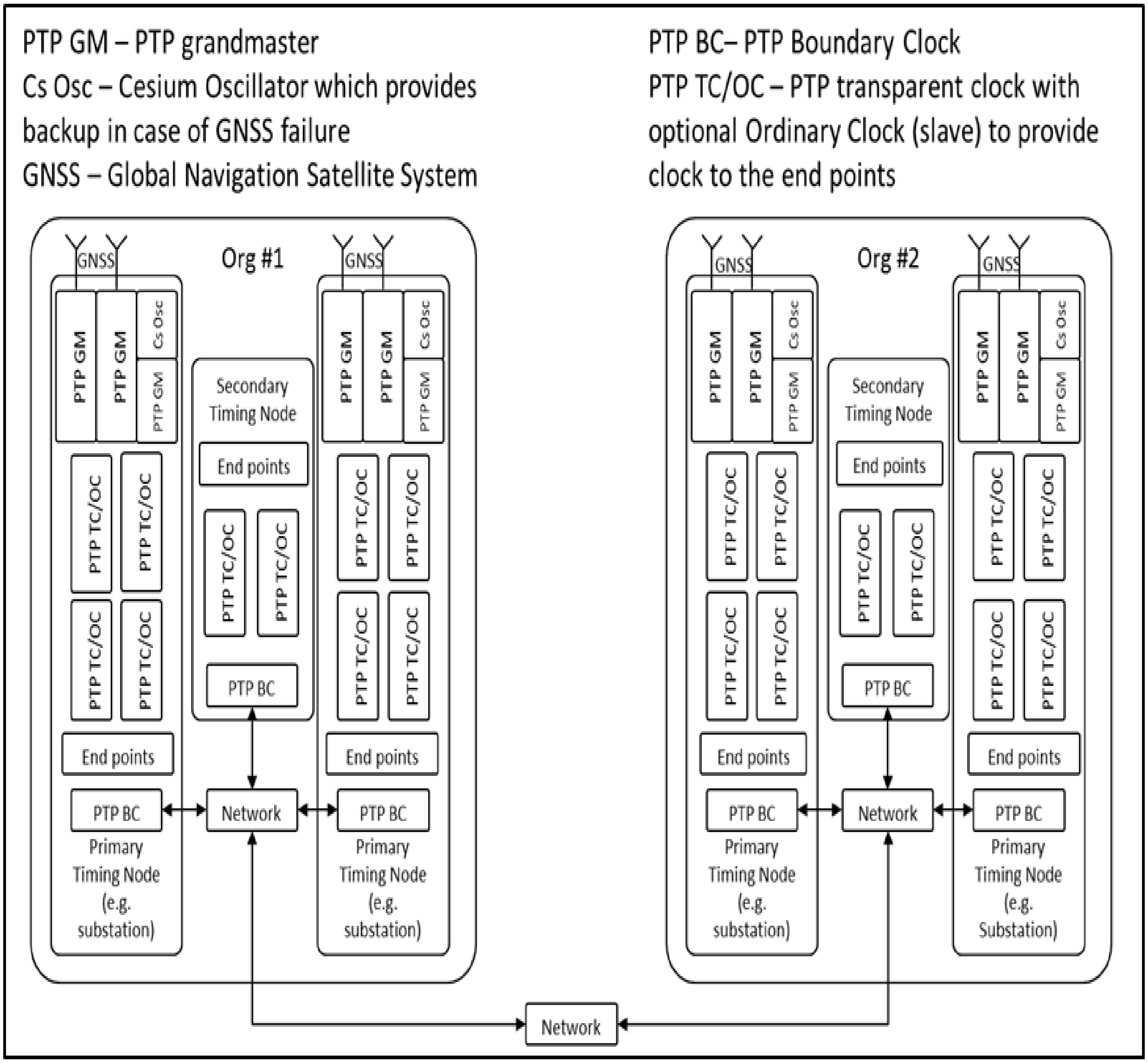

Figure 40 Wide Area Timing Distribution Architecture

Specification 11.4 details:

11.4.1 Provide time distribution at every hop in the network.

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

11.4.2.1 Measures delay over the node and inserts the information into the correction field in order to compensate for the variations in the propagation delay

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

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

11.4.4 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.

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

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

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

11.4.5.3 Receiving BC distributes time further in own organization.

11.4.6 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.

Specification 12: Data Flow Models

The specification of the data architecture includes guidelines and constructs that govern the way in which data is collected and processed, how and where it is stored, integrated and exchanged, and the forms of its use in providing resilient operations in the grid. We describe the specification in the context of the structural components in the architecture. While this document specifies the key data flows and data architecture guidelines applicable to high DER, DA, and Storage, 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.)

We use the ER description of the primary constituents of the grid as-is to outline the new data flow requirements. Figure 41 describes an as-is grid structure of today.

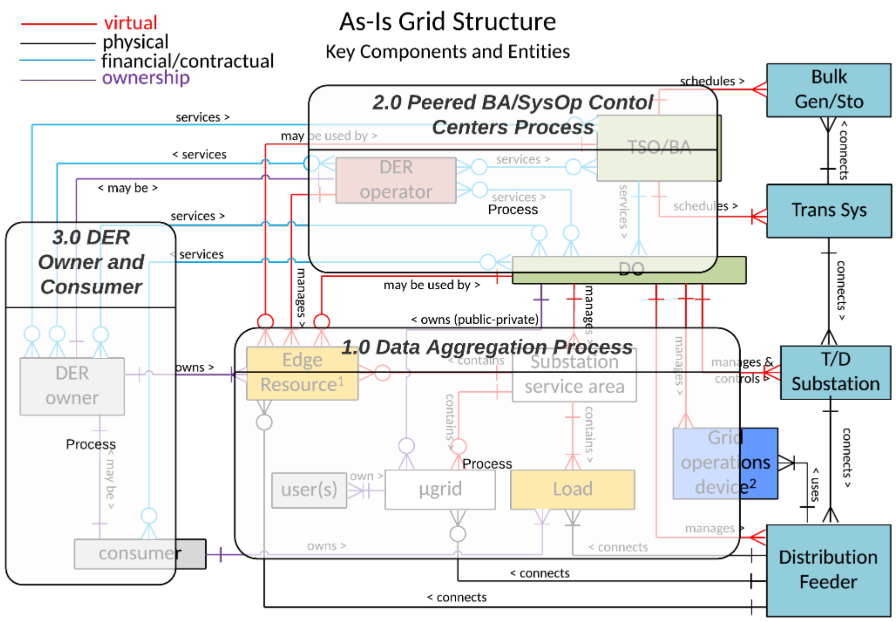

Figure 41 Data Flows Overlaid on As-Is Grid Entities

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 processes are 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.

Data Architecture Considerations

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.

Flow control and regulation via power electronics in distribution grids requires that data flows enable state information to be periodically exchanged between control points in a coordinated fashion. This information is required and used for topology identification, control signal determination and PFC connectivity to peer DERs (controlled by their own control points) and the bulk grid.

Distribution layer structure and observability platforms require a move away from siloed structures by using layers provide both redundancy (through peer to peer information exchange within a layer), and self-sufficiency with enough 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. Data carrying time distribution and synchronization are required. The observability allows dynamic changes in topology which is a condition of high DER and Storage deployments.

Storage has data flow requirements that are aligned with Specification 2 on power flow control components.

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 service.

Logical Energy Networks and distribution virtualization are 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 Volt/VAR regulation. This operation is outlined in the LEN ConOps 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.

LEN Source Decoupling Circuit Structure - as mentioned in the section on Specification 2, individual feeders and overlaid LENS can be partitioned or segmented into multiple virtual control areas or microgrids for autonomous power balancing. Between two neighboring segmentation, the PFC device state data will be exchanged in the 2.0 Peered block.

Distributed Intelligence platform and communications structures require a layered platform model to store and process data from the device hardware and sensors, firmware, operating systems, and communications systems to application devices.

Figure 42 illustrates data flows from the above architectural considerations:

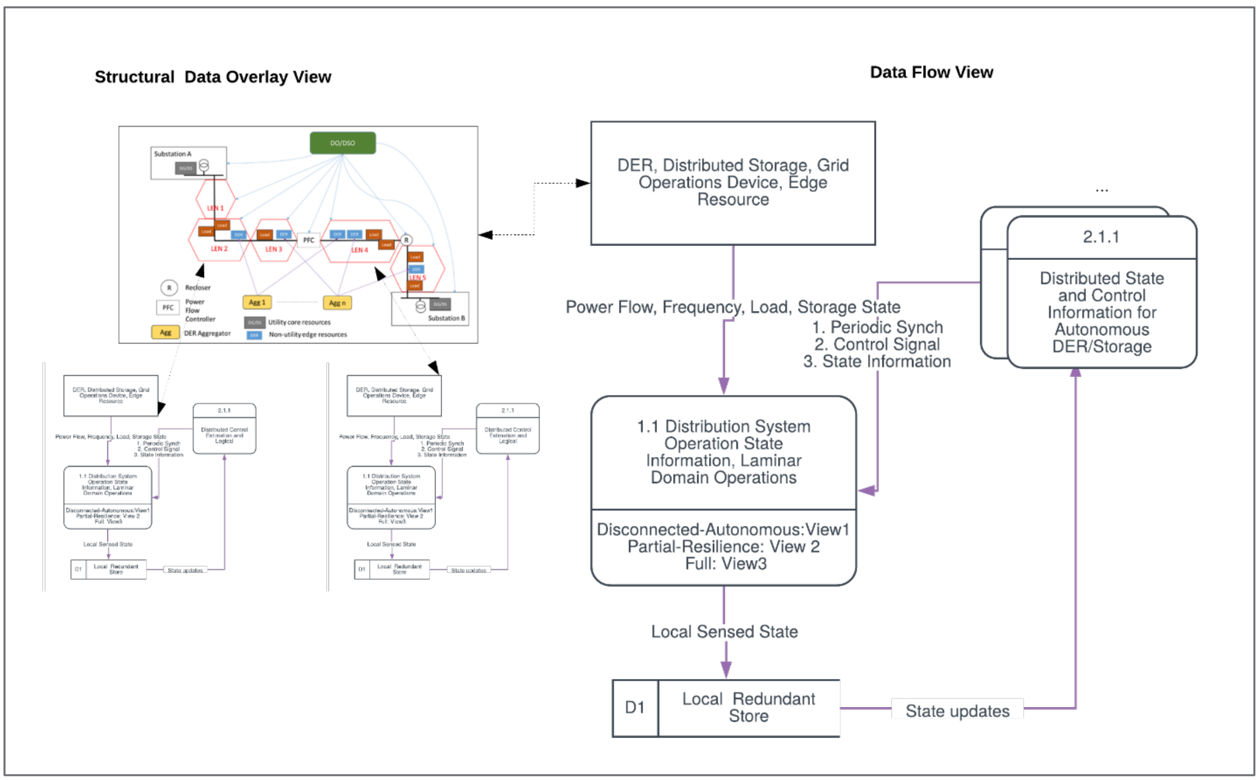

Figure 42 Data Flows for High-DER Deployments

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 right of Figure 42. The structural correspondence of multiple (potentially autonomous) DERs and Storage systems in LENs is shown on the left of the Figure 43. Data is stored locally to enable the laminar domain operations. Support for disconnected and autonomous operations control 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 a LEN module and we show the sub-component that holds the data state in block 2.1.1 (Distributed State and Control Information for Autonomous DER/Storage). This 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 supports 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 topology and control 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.

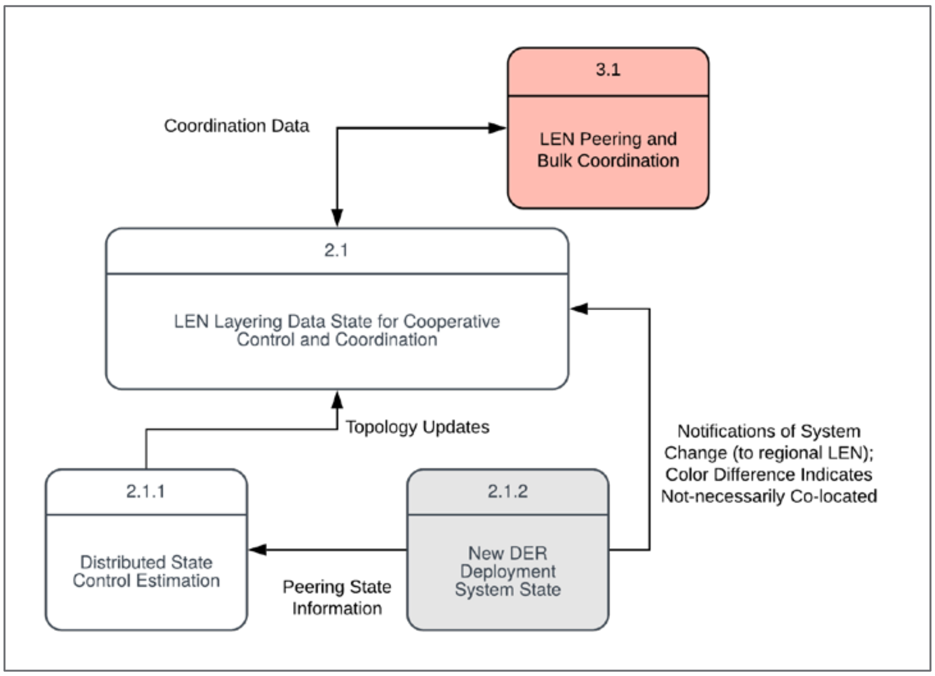

Figure 43 Data Flow Needs to Enable Coordination and Collaboration across Increasing Penetration of DERs and Storage Components

Figure 43 illustrates the new data flows that are required by the architectural recommendations with increasing penetrations of DERs and Storage in the grid. Principled data flows must be instantiated to collect the autonomous system data from control points and these data elements (represented in Figure 43 as Data Process 2.1.1) must be exchanged with LEN control points. These LEN control points enable the coordination with peering LENs shown in Data Process 3.1. Unique to this architecture is the high degree of autonomy, topology change, and power heterogeneity (in control, voltage profile, etc.) which gives rise to the systemic issues of high dynamism. To address this issue, data processes must be developed to incorporate system state change (Data Process 2.1.2) and these notifications should be exchanged with the local LEN and coordination control networks that enable LENs (for DERs and Storage) to connect with each other and the bulk grid.

The key data architecture specifications emerge from the requirements that drive the data presence near the edge of the network, high DER penetration and autonomy within LEN structures include:

Specification 12 details:

12.1 Edge devices, microgrids, DERs must retain data within an accepted resilience time window.

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

12.3 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.)

12.4 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.)

12.5 A Data flow service for eventual consistency must be implemented.

12.6 Data service must be available on DER addition/removal and topology change events and send updated data.

12.7 Control protocols must operate with partial data resident at a LEN.

12.8 Data sources should submit data, and data should be held and made available within required time constants for the correct implementation of distributed control, stress resistant, and strain tolerance algorithms deployed in the resilient grid. Ensure that timing distribution dependencies are explicit.

Specification 13: Interoperability and Grid Codes

Interoperability presumes a system of components that are connected and perform some larger coordinated function in addition to each component's local concerns and responsibilities. To make the integration of system components connect and operate more simply and reliably, an architectural focus for interoperability is the identification of well-defined interfaces and how these interfaces support a system coordination framework. This specification focuses on the interfaces for storage and customer DER.

For interoperability to be achieved in a straightforward manner, agreements on either side of the interface need to be specified and agreed to by the interacting parties. This includes clear interconnection agreements that may be specified in grid codes that are adopted in the jurisdiction of operation as well as communications interface specifications that set out the agreements on communications technology, the information being exchanged in messages, and the business processes that are supported by the exchange of messages. All of this must be accomplished within the rules of engagement set out by the business partners and those that regulate them (e.g., tariffs between electric service providers and customers).

In the high storage and DER case, a distributed control coordination framework is specified to address scaling needs and preserve rights of choice and privacy of the parties on either side of the interface.

The grid edge devices connections are depicted in Figure 44, which emphasized the principle of layered decomposition.

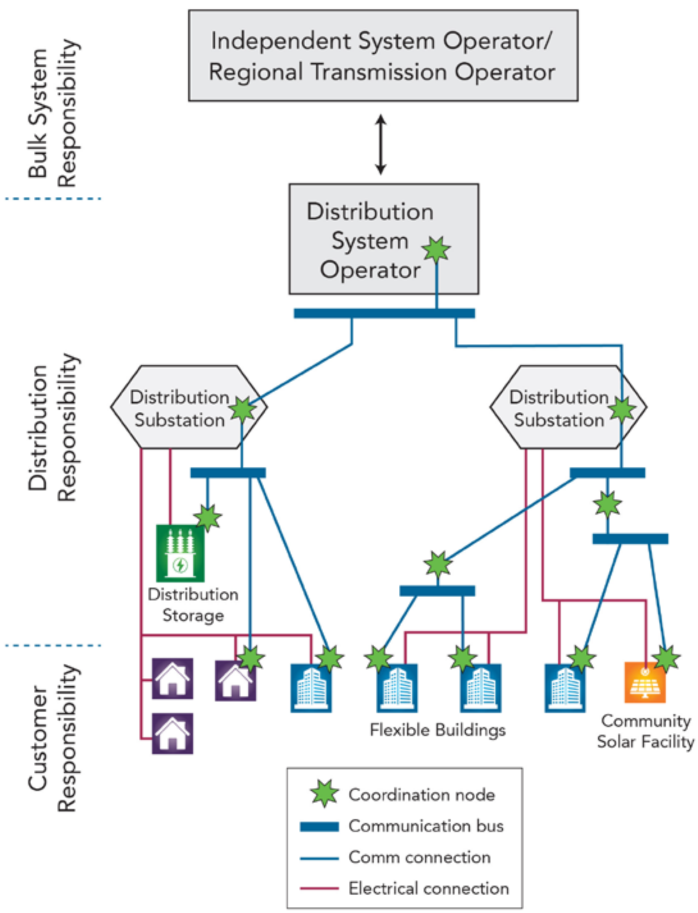

Figure 44 Architecture view with layered decomposition coordination (Interop Strategic Vision Whitepaper, March 2018)

The specification uses the concept of an Energy Services Interface (ESI), which adheres to the layered decomposition principles and is requires a service-oriented approach to defining the agreement between interacting parties. All DER can interact with similar interface agreements based on performance to service instead of technology specialization. Figure 45 provides a view of out a DER Facility that can hide the complexity of several devices and support an ESI to a variety of external actors.

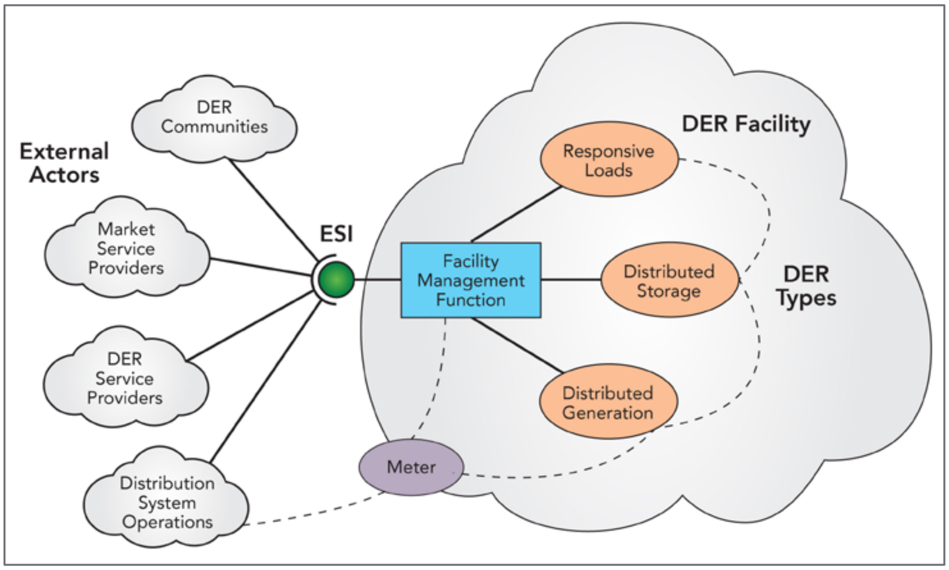

Figure 45 Visualization of a DER Facility conceptual model

Specification 13 Details

13.1 Provide clear delineation of responsibilities between the actors on either side of the interface

13.2 Adhere to layered decomposition principles

13.3 Employ a clear statement of grid codes for interconnection of DER to power system

13.4 Create a clear statement of the expected service to be performed at the interface in scheduled time, and expectation of performance (speed of response, quantity of response, quality of response)

13.5 Define a method of measurement for validation defined and the requirements of the measurement equipment (e.g., meter).

13.6 Use the 35 interoperability criteria specified in the GMLC 1.2.2 Interoperability Maturity Model

The interoperability criteria can be found in work done in the US Department of Energy GMLC Interoperability project.[47]

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 adds structural resilience.

Grid E-R structure with DSO and LENs

Figure 46 shows the revised grid E-R model for a DSO/LEN structured grid (compare to Figure 1).

[47] MR Knight, et al., A Qualitative and Quantitative Approach for Measuring Interoperability (Draft), PNNL-26412, April 2017, available online: https://gmlc.doe.gov/sites/default/files/resources/InteropIMMTool2017-04-22.pdf

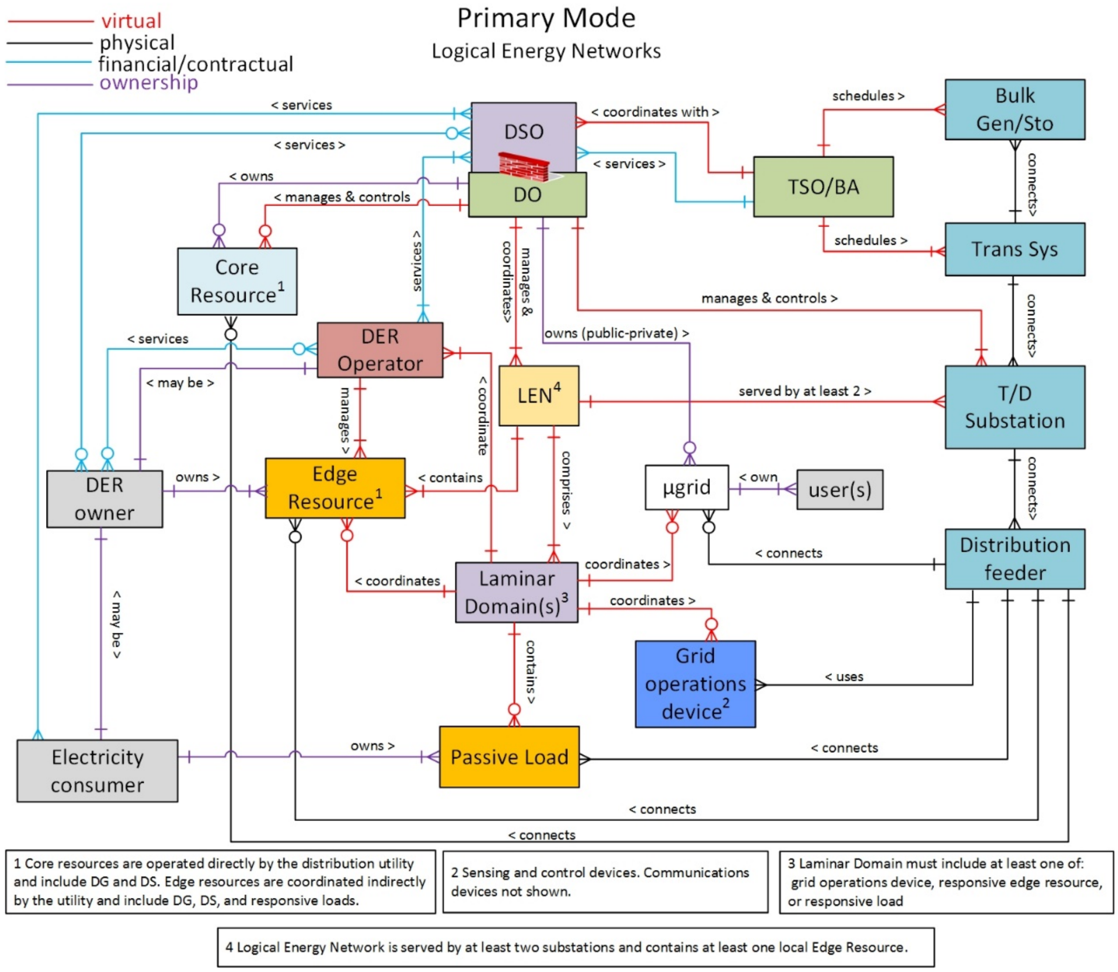

Figure 46 New LEN/Laminar/DSO-Based Grid Structure E-R Diagram

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

For the case where buildings interact with the grid, Figure 47 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.

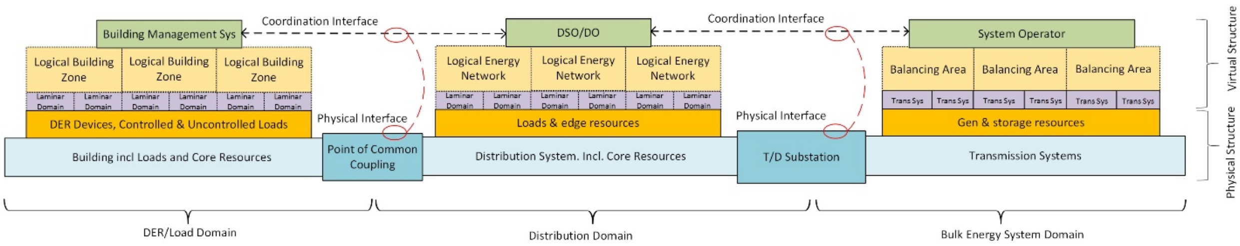

Figure 47 Triple Stack Model for New Grid Structure with Buildings

Similarly, microgrids may interact with the grid. Figure 48 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.

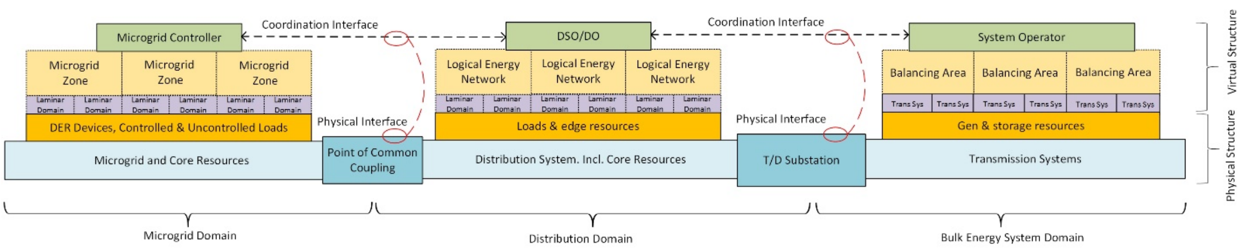

Figure 48 Triple Stack Structure with Microgrids

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

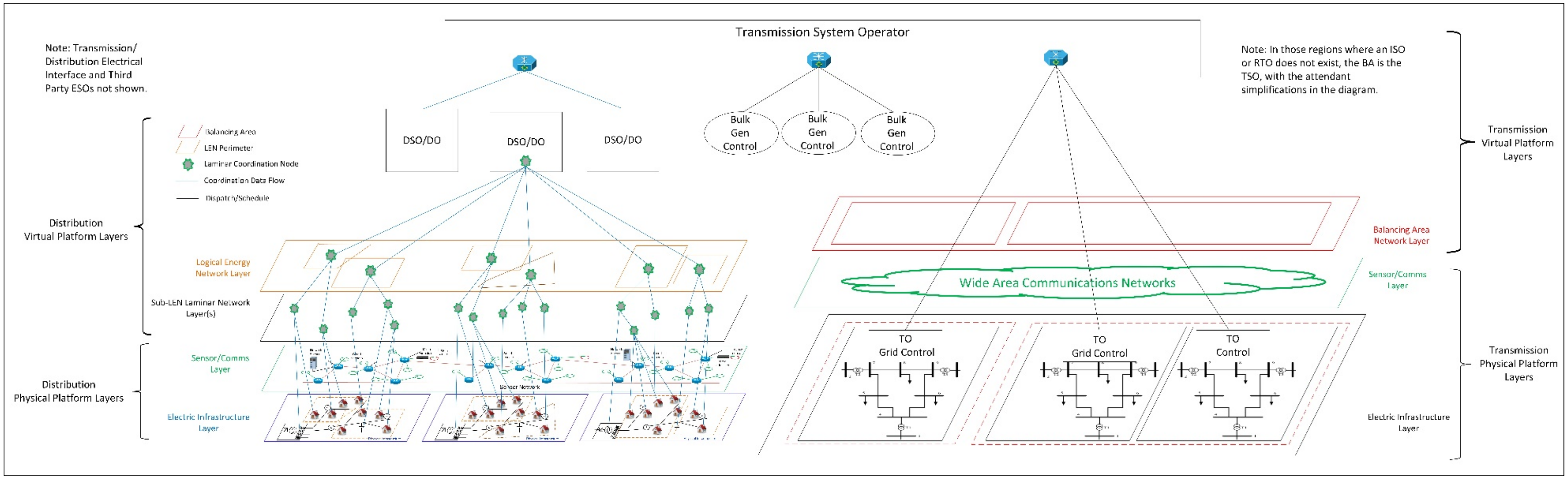

Figure 49 Composite View of Grid Structure Coordination, Control, and Communication

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 50 shows some of the logical data flow paths that may exist with ESOs.

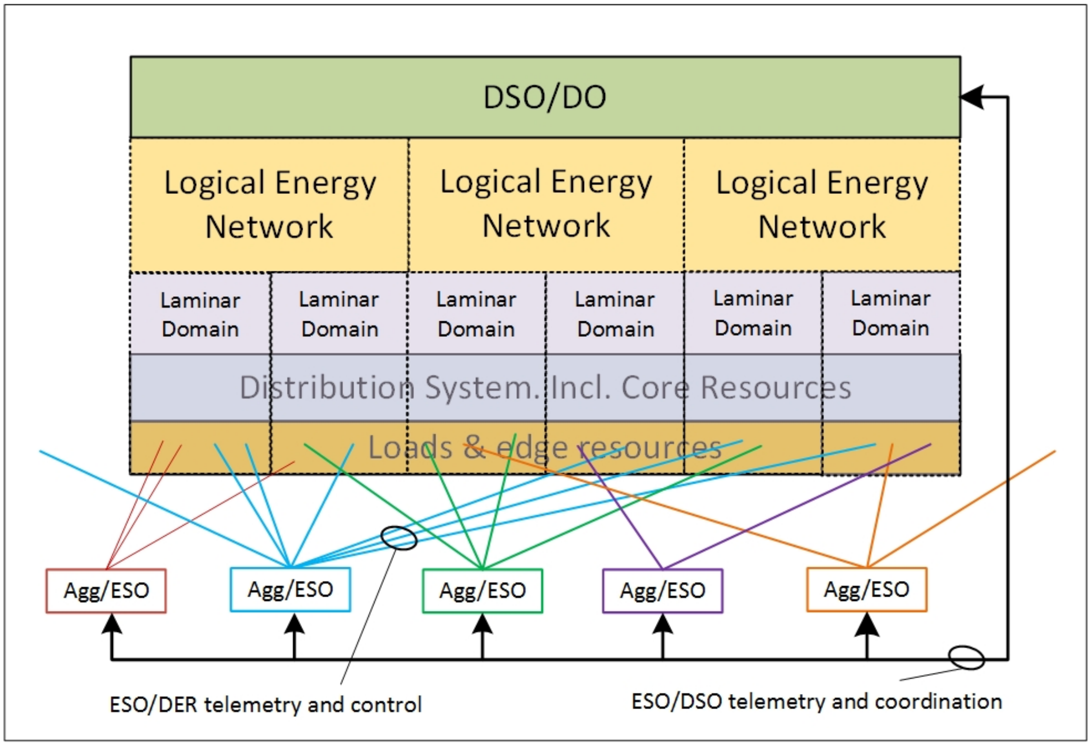

Figure 50 ESO Connection to DER and DSO/DO

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.

List of Attached Documents and Reference Papers

Document Name/File Name	Description	Version/Date
Problem Domain Reference Model – GMLC1.2.1-v2.pdf	Problem Domain Reference Model Document	11/2019
Entities.Definitions.01.09.2019.xlsx	Utility Industry Entities list	January 2019
CA focused industry structure model ER.vsd	CA-type industry structure model	
EmergingTrends_Systemic Issues_Grid v4.0.pdf	Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid report	
NY Industry Structure Diagram_v1.2.vsd	New York Industry Structure Model diagram	
NY Industry Structure Diagram_v1.2.xlsx	New York Industry Structure Model spreadsheet	
ERCOT Industry Structure Diagram_v1.vsdx	ERCOT Industry Structure Model diagram	
ERCOT Industry Structure Diagram_v1.xlsx	ERCOT Industry Structure Model spreadsheet	
ERCOT Market Control_v0.1.vsdx.	ERCOT Market-Control Process Chart	
PNW Industry Structure Diagram_v1.vsdx	Pacific Northwest Industry Structure Model diagram	
PNW Industry Structure Diagram_v1.xlsx.	Pacific Northwest Industry Structure Model spreadsheet	
Regulatory Structure Model.vsdx	US Electric Sector Regulatory Structure Diagram	
Grid Architecture Component Class Specification – Storage v0.2	Storage Component Model	
Grid Architecture Component Class Specification – Microgrid v0.1	Microgrid Component Model	
Grid Architecture Component Class Specification – Digital Communications Network v0.1	Communication Network Component Model	
Grid Architecture Component Class Specification – Grid Sensor v0.2	Grid Sensor Component Model	
Grid Architecture Component Class Specification – Inverter	Inverter Component Model	
Grid Architecture Component Class Specification – Load	Load Component Model	
Grid Architecture Component Class Specification – Power Flow Controller	Power Flow Controller Component Model	
Grid Architecture Component Class Specification – Solar PV	Solar PV Component Model	
Grid Architecture Component Class Specification – Electric Vehicle	Electric Vehicle Component Model	
08447750.pdf	On a Future for Smart Inverters and Integrated System Functions	Dec 2018
high_DER_DA_St_v1.pdf	High DER/DA/Storage Architecture Circuit Structure and Power Flow Control	

Document Name/File Name	Description	Version/Date
cdc2016.pdf	Optimal Placement of Energy Storage in Distribution Networks	Oct 2017
LEN ConOps v0.3.pdf	Logical Energy Networks Concept of Operations	Jan 2019
grid-forming.pdf	PowerPoint Presentation on Grid Forming Inverters	June 2019
layering.pdf	Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures	Jan 2007
alternativedecomp.pdf	Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications	Dec 2007
EV Charging Station Trend.pptx	PowerPoint presentation on EV Trends	May 2019
firefly synch paper.pdf	Firefly Synchronization with Phase Rate Equalization and Its Experimental Analysis in Wireless Systems	2016
GMLC_GA4B_F.pdf	Grid Architecture for Buildings	Dec 2019
Littelfuse_EVI_EV_Charging_Infrastructure_Presentation.pdf	EV Charging Infrastructure	April 2019
Grid Edge VVC Paper – IEEE T&D.pdf	Grid Edge Control: A New Approach for Volt-VAR Optimization	Nov 2015
Joint CA IOU SI White Paper.pdf	Enabling Smart Inverters For Distribution Grid Services	Oct 2018

2016

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
V0.2	1/14/2019	Updated grid structure ER diagrams and added data architecture section; resolved citation references.	GMLC 1.2.1 team
V0.3	12/1/2019	Documents table filled out	GMLC 1.2.1 team

GRID
MODERNIZATION
LABORATORY
CONSORTIUM
U.S. Department of Energy

902 Battelle Boulevard

P.O. Box 999

http://gridmodernization.labworks.org/