Grid Architecture Specification: Variable Structure Grids

GMLC 1.2.1 v0.4

October 2019

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Grid Architecture Specification

View Designation: GMLC 1.2.1 Variable Structure Reference Architecture v0.4

Structure Types:

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

Perspective Types

	Demand/Supply Flow		Industry Structure		Value Flow
x	Grid/Circuit	x	Sensing & Measurement	x	Data Mgmt./Data Flow
	Analytics/Visualization		Control/Coordination		Protection
x	Communication Networks		Timing Distribution		Cyber-Security
	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 in which electric circuit infrastructure is adjustable, reconfigurable, or otherwise changeable in terms of topology and control.

Glossary

BPS – Bulk Power System

C&I – Commercial and Industrial

DA – Distribution Automation

DER – Distributed Energy Resource

DO – Distribution Operator

DSO – Distribution System Operator

FAN – Field Area Network

FLISR – Fault Location, Isolation, and Service Restoration

NAN – Neighborhood Area Network

ICT – Information and Communication Technology

LEN – Logical Energy Network

PFC – Power Flow Controller

T/D – Transmission/Distribution

ULS – Ultra Large Scale

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

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:

- Flow management and FLISR in partially meshed distribution circuits
- Operation of networks of microgrids
- Dynamic adaptive grid re-structuring for resilience events
- Operation of distribution grids as networks for energy transactions

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

Business Context, Entities, and Relationships

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

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

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

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**,[1] 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

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

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 significant increases in operational flexibility of grids, especially distribution grids by clarifying and generalizing the concept of variable structure at the physical and logical levels
2. Clarify and expand the control stack and coordination structures needed to enable variable grid structure.
3. Provide support for the Logical Energy Network concept found in the High Resilience and High DER Penetration reference architectures.

Variable grid structure may be used as either a continuation of the LEN concept, or as a standalone reference architecture, independent of grid virtualization.

Core Variable Structure Architecture Principles

1. Variable grid structure is a multi-scale structure concept. It may be applied at all levels from microgrid to regional grid.
2. Variable grid structure has a physical aspect and a logical or virtual aspect.
3. Virtual grid structure may be viewed as a set of power flow digraphs. We may view the grid at the virtual level as being multiple grids operating independently, each ultimately supported by the underlying physical grid.
4. The set of virtual power flows must be resolved into a single power flow at the physical level. This resolution must conform to the constraints of the physical grid, including not just connectivity, but also protection, thermal, and voltage constraints.
5. Variable grid structure is an aspect of "horizontal" structure; that is, it refers primarily to the electric infrastructure layer. The relationship to vertical structure (such as with coordination frameworks) requires a mapping to exist to the physical layer from the virtual level and a coordination/control structure to implement the mapping.
6. Variable grid structure may be used directly, or with Laminar Networks or with Logical Energy Networks.

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.[1]

ULS normal failures approach – applying Ultra-Large Scale system theory[2] 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

[1] 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

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

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.

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

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

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

Multi-Scale Structure – Scalability is always a consideration in developing systems for the grid. In the case of grid structure, it refers to the use of structures that apply equally well at any grid scale, from microgrid up to regional interconnection. We refer to such structures as multi-scale structures, and using such structures is a means of achieving conceptual integrity for the architecture, specifically under the principle of solving similar problems in similar ways.[1]

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

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

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

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.[1] The use of a sensing and communications layer facilitates variable grid structure.

Architecture Specifications

The architectural views are presented in terms of (black box) components, structures, and externally visible characteristics.[2] 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 – Microgrid v0.1

Grid Architecture Component Class Specification – Power Flow Controller

Grid Architecture Component Class Specification – Digital Communication Network

[1] 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

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

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.

<u>Abstract Model</u>

Figure 1 shows the general abstract model for variable structure grids. The model is divided into physical and virtual portions.

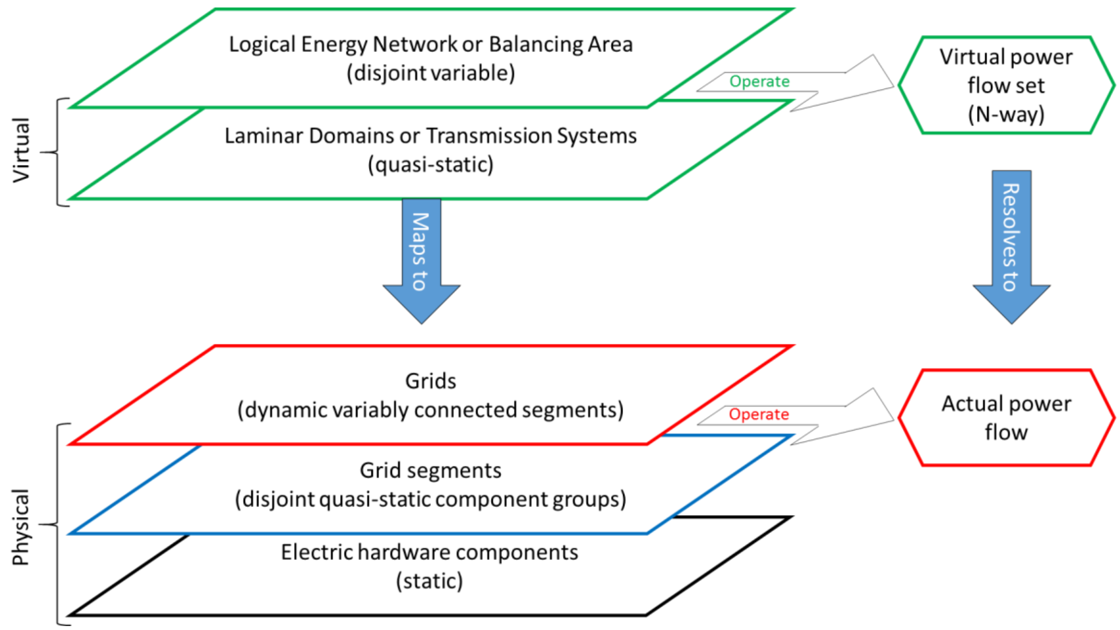

Figure 1 General Abstract Model for Variable Structure Grids

Note that this is a multi-scale structure model.

<u>Single Structure Views</u>

This section provides a number of single structure specifications. Each focuses on a specific structure class from the standard set: electric infrastructure, ICT superstructure, coordination framework, and control structure.

Specification 1: Electric Circuit Structures

At the transmission level, circuit segmentation occurs at the substations and switching stations, with switchgear as the connecting elements. Control of structure is performed via SCADA-based control. This form of variable grid structure is well established and will not be further detailed here. It is worth recalling however, that variable grid structure is a multi-scale concept. Transmission/distribution interface substations are points where, from a transmission level point of view, connections exist to whole distribution system service areas, which at the transmission level can be viewed as single components attached to the transmission grid. The switchgear in the substation is the connector by which grid structure can be modified – by connecting or disconnecting whole distribution system service areas. At the level of the distribution system, the grid segment concept applies again in a recursive manner. Figure 2 illustrates a multi-scale view of grid segment structure.

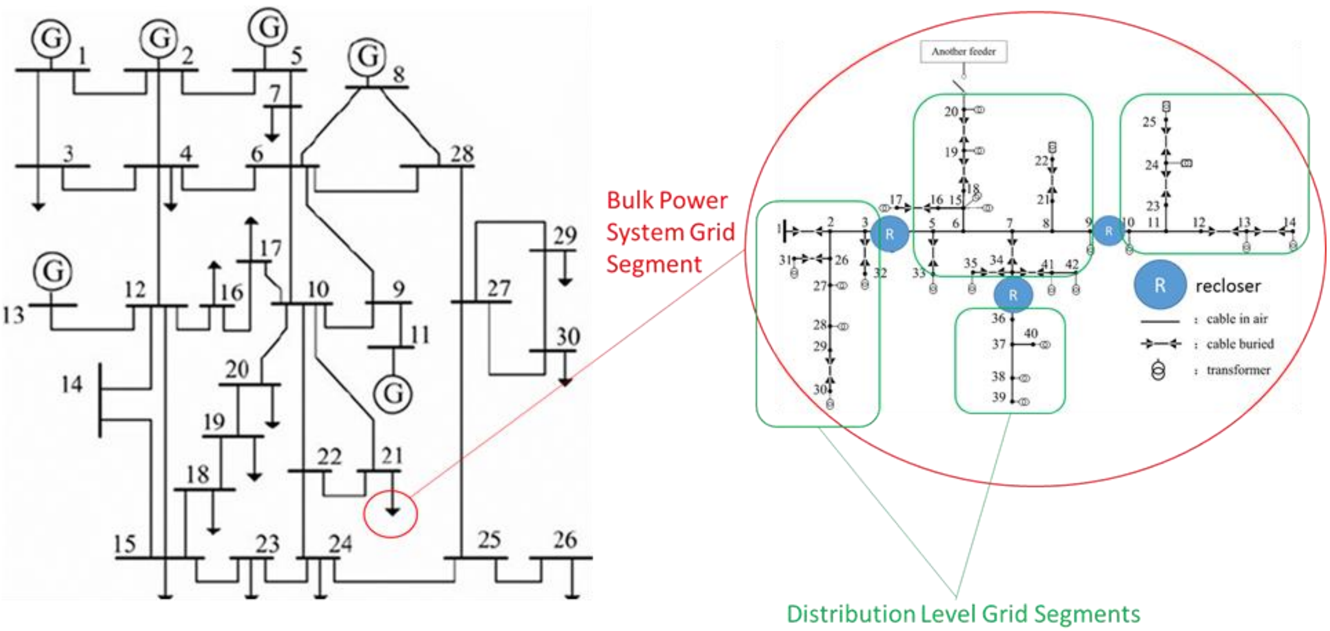

Figure 2 Multi-Layer View of Grid Segmentation

Distribution level variable structure has been more ad hoc in nature that transmission structure, but variable structure exists in in many distribution systems in one form or another, mostly with partially meshed distribution feeder primaries. Figure 3 shows an example of partitioning of a portion of a distribution system to make use of variable structure. Note that the circuit segment between connectors C2 and C3 can be switched to “belong” to either Substation 1 or Substation 2, as is commonly done for partially meshed feeders. Later figures will illustrate the application of Laminar Networks and Logical Energy Networks to this variable structure.

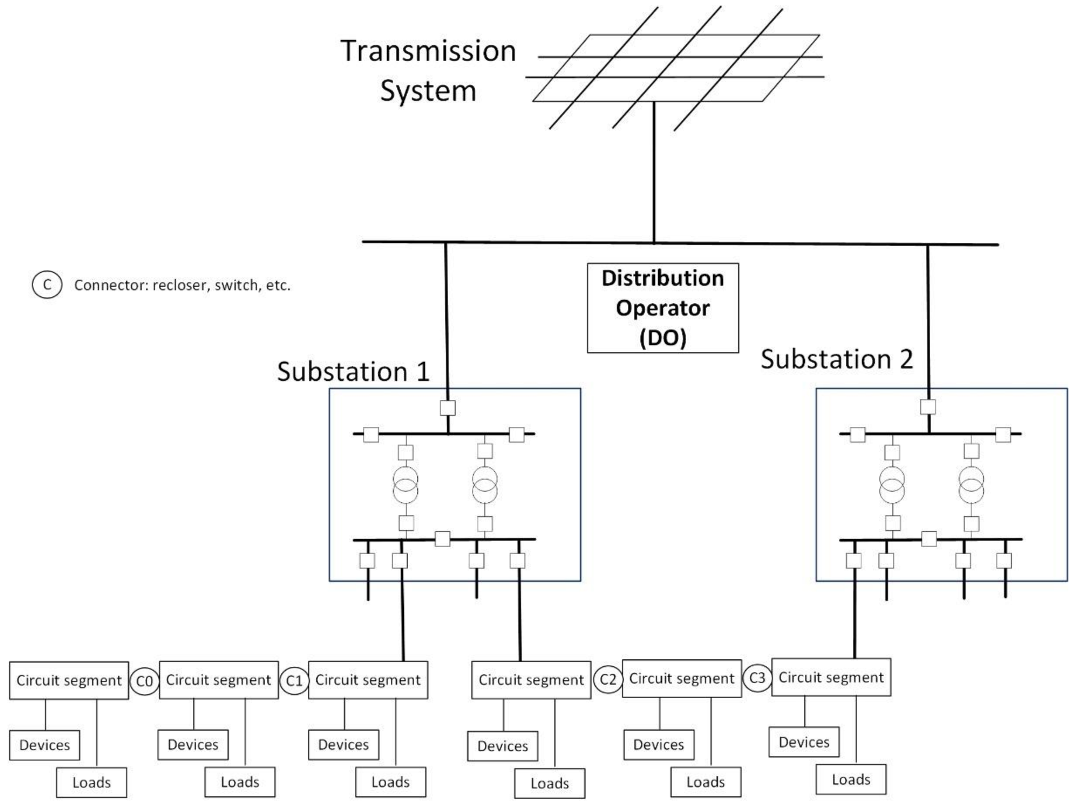

Figure 3 Distribution Circuit Segment Structure

The connectors (C0-C3) can be any type of circuit switching device: recloser; switch; sectionalizer; even a power flow controller (PFC) if it is being used to completely cut off power flow. The underlying physical circuits, sensor, and control devices are treated as being essentially static on operational time scales. This strcture (the *as-built* structure) can be changed but only very slowly (maintenance and planning time scales).

Sets of electric circuit components are grouped together to form grid segments. Segments are generally bounded by connecting devices. Grouping of circuit elements into segments is a planning and field engineering function which can be changed somewhat more easily than basic circuits, and so is classified as quasi-static.

Where grid segments are joined by connectors, the *as-operated* structure may change more quickly, especially if the connecting devices are automatically or remotely operated. It is the as-operated structure that is variable (on operational time scales) and so is classified as dynamic structure. Note that connections of non-utility edge devices to the grid involves switching (or connection via inverters that can disconnect from the grid) and so are part of the grid's variable structure. Power flow controllers may affect grid structure in two ways as shown in Figure 4: by disconnecting edge-attached devices such as DER, or by disconnecting internal portions of the grid.

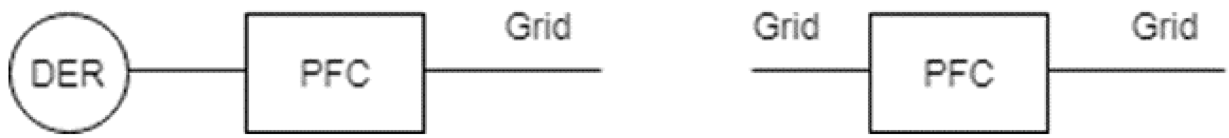

Figure 4 Two Methods for Using PFCs as Segment Connectors

In a grid that has a high penetration of power flow control devices, appropriate control of these devices can result in considerable structural flexibility, as indicated in Figure 5.

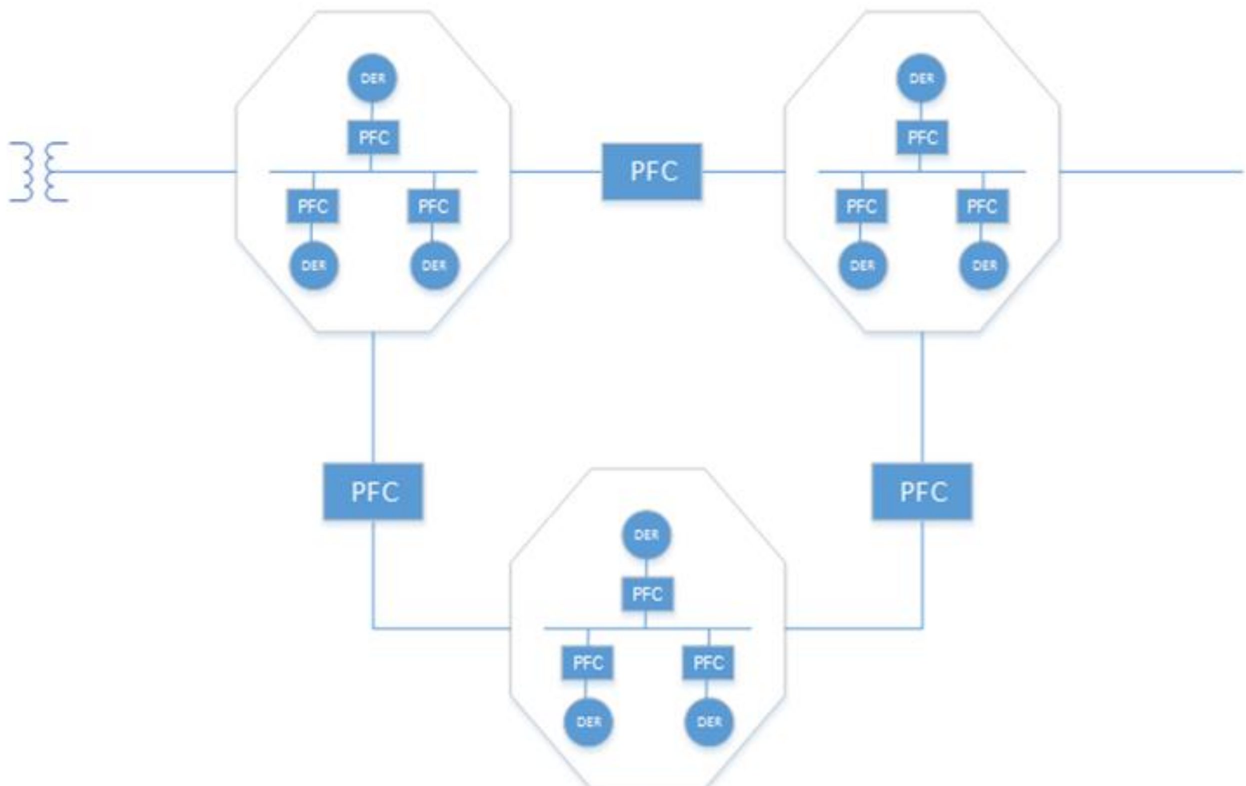

Figure 5 Example High Penetration of PFC Devices in Grid Structure

Specification 1 details:

1.1 For operational purposes, treat as-built physical circuit hardware as a static structure.

1.2 Organize power circuits into segments comprised of disjoint sets of electrically connected components, bounded by switchable "connectors."

1.3 Connectors are power circuit switching devices such as switchgear, reclosers, sectionalizers, and protective devices; also power electronics devices to the extent that they can cut off power flow. Note that merely adjusting flow is not a structural change.

1.5 Circuit segments are quasi-static on operational time scales. Circuit segment definitions do not change as part of real time operations. Circuit segment definition is a planning and engineering function.

1.7 Circuit segments are connected together to form variable structure grids. Connector switching provides the structural variability.

Specification 2: Distribution Sensing and Communications Layer

The layering and platform concepts are applied to electric infrastructure, sensing and measurement, and communications for electric distribution to define a platform for flexible electric distribution operations. Layering and consequent decoupling of applications enhances configurability, functional flexibility, and functional extensibility.[1]

Note that the sensing and communications structure is static in the same sense as the physical circuit layer (electric hardware components). Consequently, the circuit hardware and the sensing/communications layer can be treated together as a platform.[2]

Sensing and communications are associated with the base electric circuit hardware. This means that the physical sensing and communications layer is also static for purposes of variable grid structure. Figure 6 illustrates the concept of combining electric circuit infrastructure with sensing and communications networks into a layered platform with static stucture.

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[1] 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

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

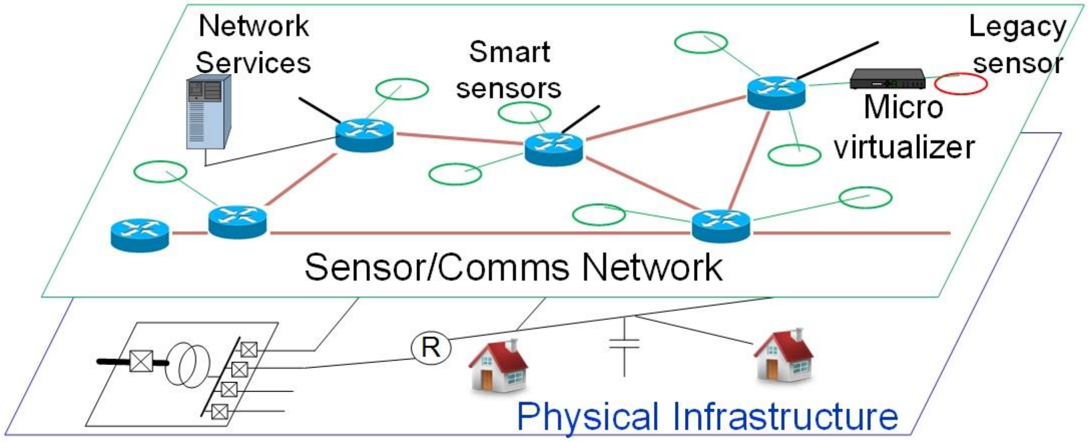

Figure 6 Electric Circuit and Sensing/Communications Layering

With most modern communications networks, data flows can be complex, so the *logical* view of communications can be variable in structure, due to the routing capabilities of the communication network.

Specification 2 details:

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

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

2.3 Combine the electric distribution layer and the sensor/communications layer to form a structurally static distribution platform.

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

2.5 Enable data flows among grid segments as needed by using data streaming and publish/subscribe network mechanisms and protocols.

2.6 Circuit electrical protection and control devices may be included in the static distribution platform.

Specification 3: Coordination of Variable Structure Distribution Grids

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 network utility maximization via layered decomposition.[1] The resultant structures are called Laminar Coordination Networks. Figure 7 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.

The Laminar Coordination Framework provides a means to coordinate elements of circuit segments. Such a framework can be quasi-static in the same sense as the grid segments, or can be dynamic (with some attendant complexity – Laminar network structure may have to follow grid structure changes). It can also structurally static when combined with well-chosen LENs (see Specification 4 below).

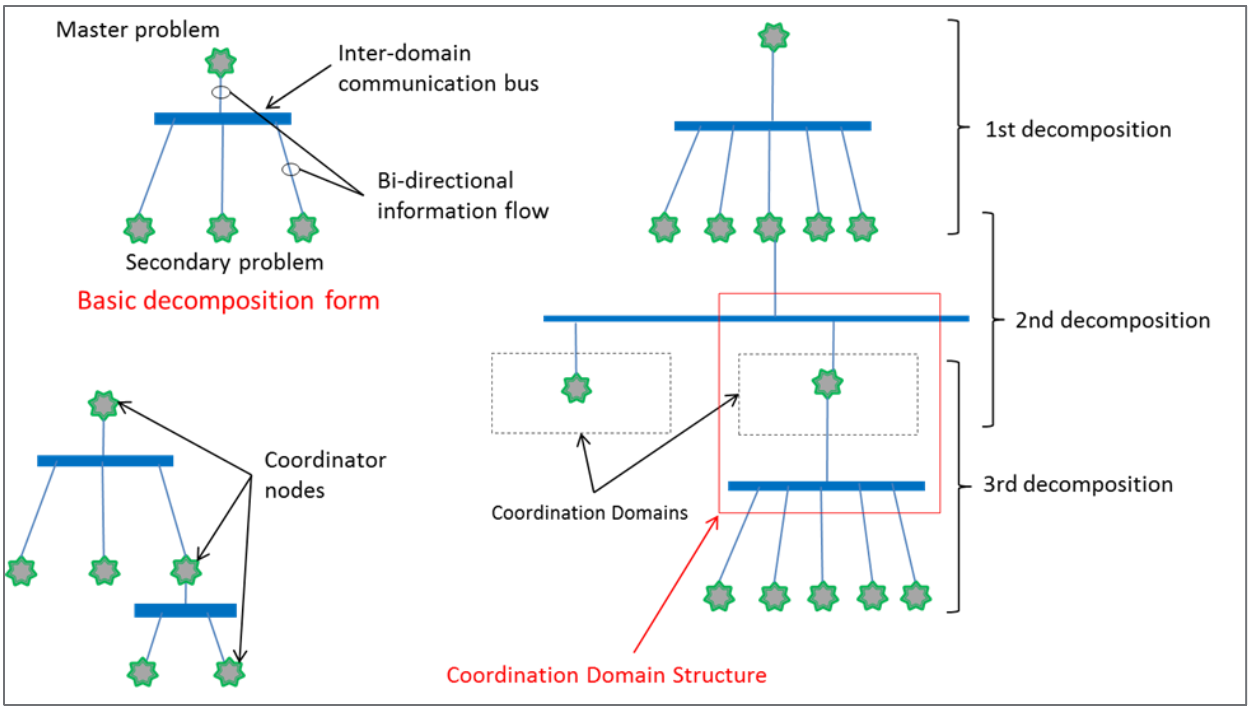

Figure 7 Laminar Coordination Framework Structural Elements

Each Laminar coordination domain contains a Domain Coordination Node, an intra-domain communication bus, any devices to be coordinated, the computing elements (hardware and software)

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[1] 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 .

needed for both the Coordination node and the local applications (analytics, control, etc.) and northbound and southbound communication interfaces.

As with structurally static grids, Laminar Networks can be mapped to grid structure. Figure 8 below shows a three tier mapping starting at top with the Distribution Operator control center and continuing down through the substations to the circuit segment connectors and the individual devices at the circuit level. With this approach, an issue arises when a circuit segment (typically a circuit section) is switchable to “belong” to any of two or more different substations. In practice we want the laminar chain to fit within the substation service area with this approach, but the circuit segment between connectors C2 and C3 may be switched to belong to either Substation 1 or Substation 2. Since a Laminar node can have only one parent at any given time, coordination can be resolved one of two ways in this approach:

1. Coordination for the circuit segment can be done via interaction between substation Laminar nodes (note that some utilities do not allow inter-substation communication for security reasons)
2. The link(s) from the segment devices can be switched to follow the circuit structure in real time

Each approach can work but has disadvantages – the first introduces extra latency and the second introduces extra logic complexity in adjusting the Laminar Network structure in real time. There is nothing fundamentally wrong with either approach, but having a *static* Laminar Network structure is desirable.

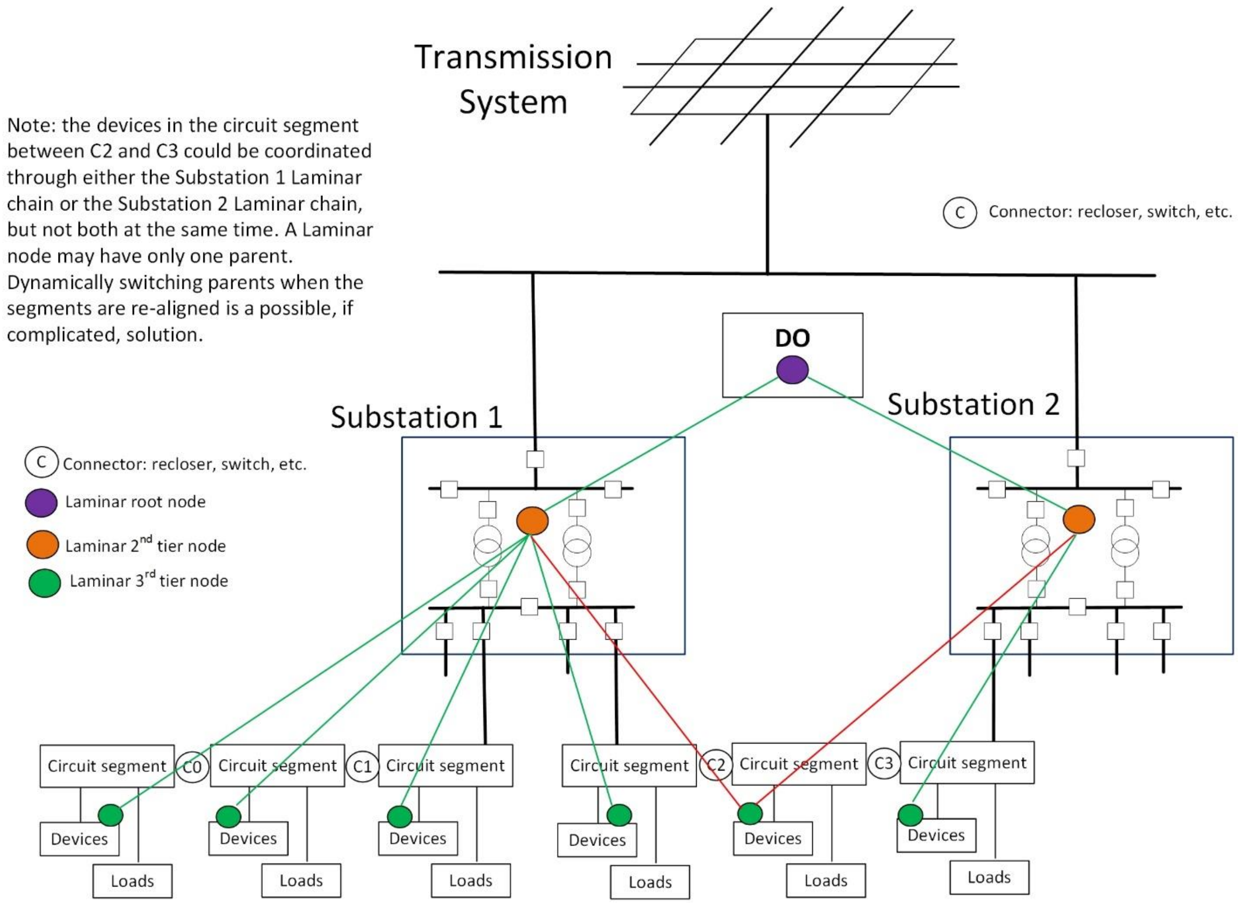

Figure 8 Example Three Tier Laminar Coordination Structure (Connector Control not shown)

In the diagram of Figure 8 the links shown in red are the two versions that would be needed if dynamic Laminar structure is used to match underlying dynamic circuit structure. In practice only one of these would be in use at any time and when the circuit segment is switched from one substation to another the Laminar link must also be switched to match.

Another issue with this approach to mapping the Laminar Network is that the fan-out from substations nodes to circuit device nodes can be large. This can be addressed by introducing more layers in the Laminar Network.

Specification 3 details:

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

3.2 Follow the Framework to define logical information flows for the coordination process. This means no tier bypassing, gapping, or structural hidden coupling (nodes with multiple parents).

3.3 Laminar coordination structures are multi-scale and should be complete, meaning that the structure should have full vertical span. This means that coordination should not change from Laminar at some levels to some other approach at other levels (such as ad hoc cellular interaction rules).

3.4 Plan the Laminar Framework to be structurally static where possible.

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

Specification 4: Virtualization of Variable Structure Distribution Grids

A Logical Energy Network (LEN) is a distribution level virtual structure defined and enforced through coordination and control processes. It is a portion of a distribution system that is partitioned 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 maps to a portion of a primary feeder, with its associated devices, sources, and loads. Ideally, each LEN has three types of energy sources available to it:

- Feed 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 provides:

- Local balance and power wheeling
- V/VAR regulation (local)
- Grid services resource management (local)

If islanding is possible, then internal stabilization, frequency regulation, and (re)synchronization with the grid are needed as well. Networked microgrids[1] can be treated as LENs.

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 9 shows a distribution feeder with LEN virtual structure superimposed.

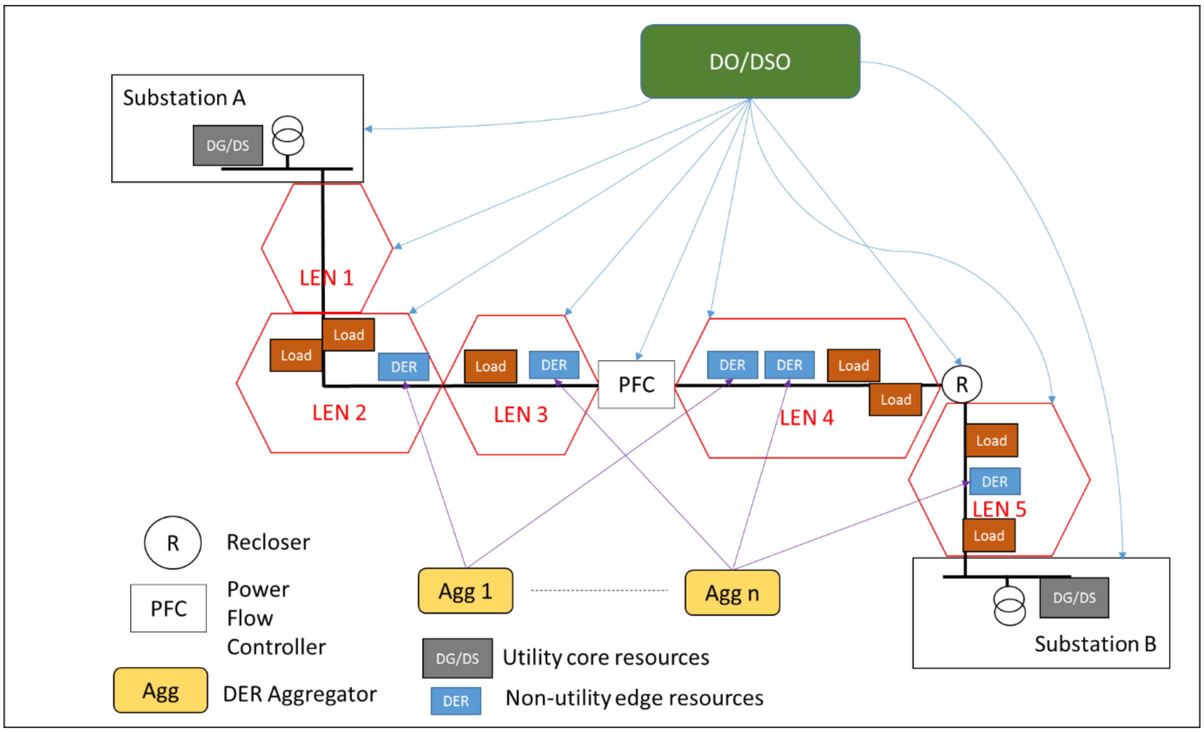

Figure 9 Example Feeder LEN Structure

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

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

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[1] F Zhang, et al., Operation of Networked Microgrids in a Distribution System, CSEE Journal of Power and Energy Systems, Vol. 1, No. 4, December 2015, pp. 12-21,available online: https://ieeexplore.ieee.org/document/7377164

Note that LENs are compatible with Laminar Coordination. Each LEN can function as a Laminar Coordination domain and the Laminar node can coincide with and be hosted on the same computing element as the LEN logic. Figure 10 illustrates and example of LENs definitions in combination with a Laminar Coordination Network mapped to a portion of a variable structure distribution grid. Note that in this example, the Laminar Network has been connected to the segment connectors. This will be discussed in more detail in the section on Structure Control. Also note that the grid segment in LEN 0 has enough devices to justify adding a fourth Laminar layer.

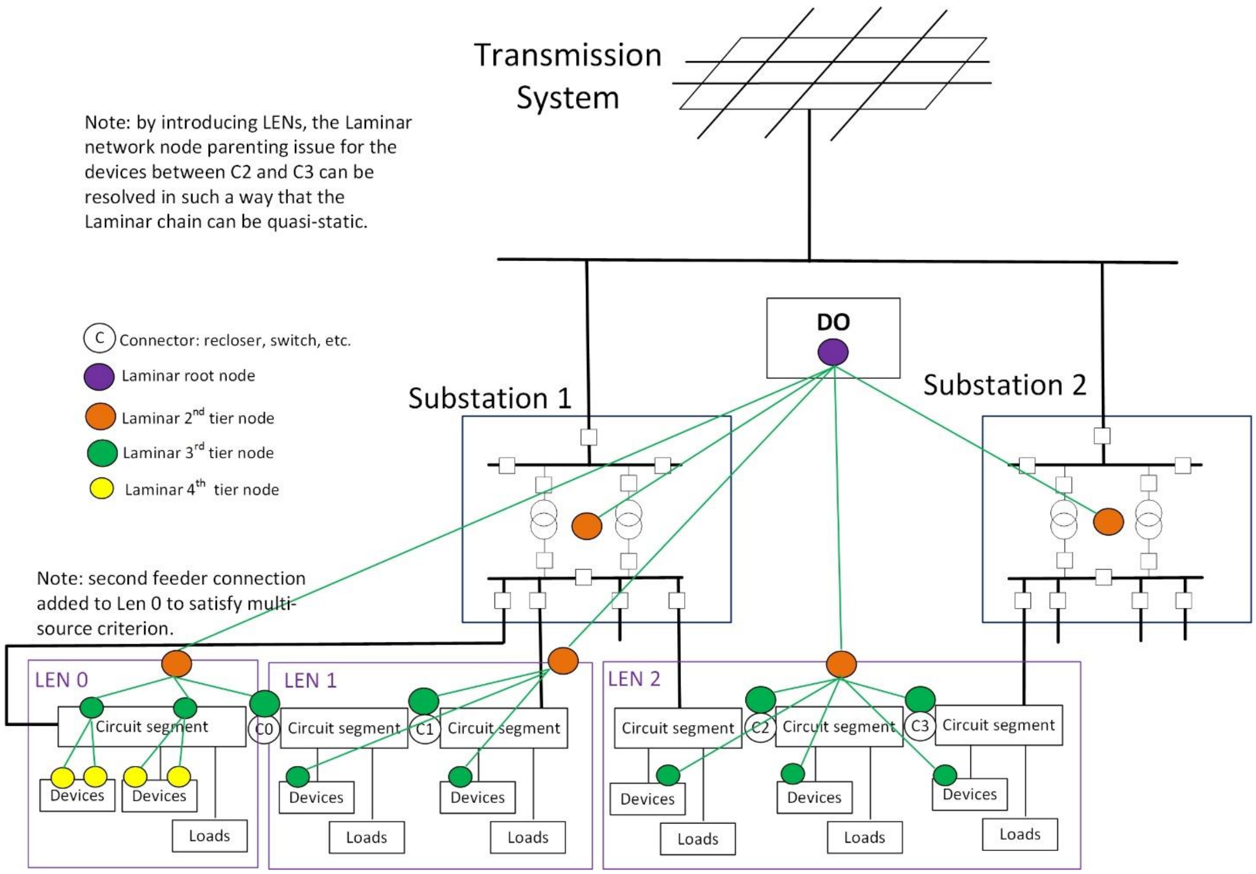

Figure 10 Combined Segment, Laminar, and LEN Structure

The relationship between Laminar Networks and LENs can be exploited to solve the problem of keeping the Laminar structure static. In this case, LEN 2 has been defined in such a way that the circuit segment that formerly (see Figure 8) had to be switched between two substations is included in a single LEN, whose 2nd tier Laminar node (orange) is the single static parent of the lower level nodes. The LEN spans the set of circuit segments and the LENs are now at the same tier level as the substations, making substations and LENs coordination peers. This eliminates the need to switch Laminar links between parent nodes, making the Laminar Network structure static.

Specification 4 details:

4.1 Each distribution system can be comprised of a set of non-overlapping, contiguous Logical Energy Networks.

4.2 A LEN does not have to be bounded at grid segment boundaries, but splitting a segment over two or more LENs introduces extra complexity in mapping a coordination framework to these structures. Absent a compelling circumstance, LENs should be bounded by segment boundaries.

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

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

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

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

Specification 5: Control of Variable Grid Structure

At the BPS level, structure control is integrated with other aspects of system control, such as dispatch and balance. At the distribution level, structure control has typically been handled in a more siloed manner, with some control being done for purposes of congestion management and some for purposes of fault isolation, maintenance, etc. Much of the structure control is done either manually or via manually-invoked remote control (the exception being some forms of automatic FLISR).

As distribution systems become more dynamic (more changeability and behavior on shortening time scales) grid structure control must become more integrated with general grid management and control. In particular, as distribution systems move toward serving as networks to facilitate energy transactions, DER penetration, and non-wires alternatives, and as electric grids converge with other infrastructures (gas, water, transportation, district heating/cooling, etc.), grid structural control must become part of a simultaneous solution to power flow, Volt/VAR regulation, frequency regulation, stabilization, synchronization, load sharing, energy storage management, and protection. Maximizing the effective capacity of the distribution system will mean continually determining the structural configuration simultaneously with the power flow solution. Whether this is done in a centralized fashion or a distributed fashion is an engineering matter. However, either approach has implications for availability of certain kinds of information about circuit structure and structure state (connector settings) and therefore data flow models. As implied in Figure 11, multiple time scales are involved, and a process for resolving a set of proposed virtual power flows into a specific real power flow must include grid structure when grid structure is variable.

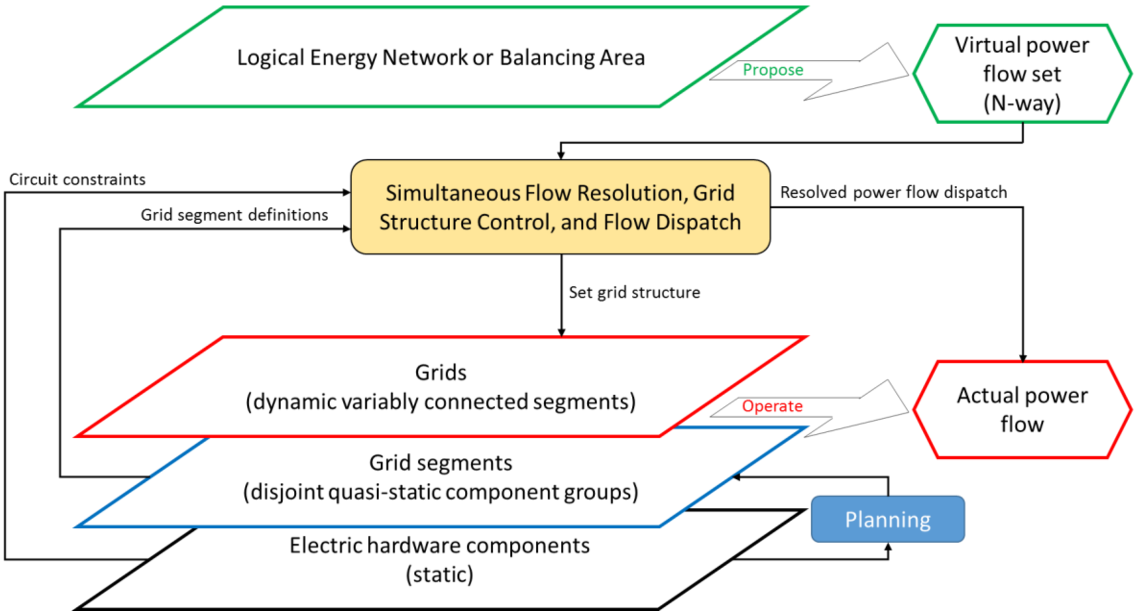

Figure 11 Variable Structure Abstract Model with Structure Control

One approach to grid structure control is to use a control form similar to what is used now, which is a centralized control. Figure 12 shows the most basic arrangement, which maps well to conventional SCADA-type control.

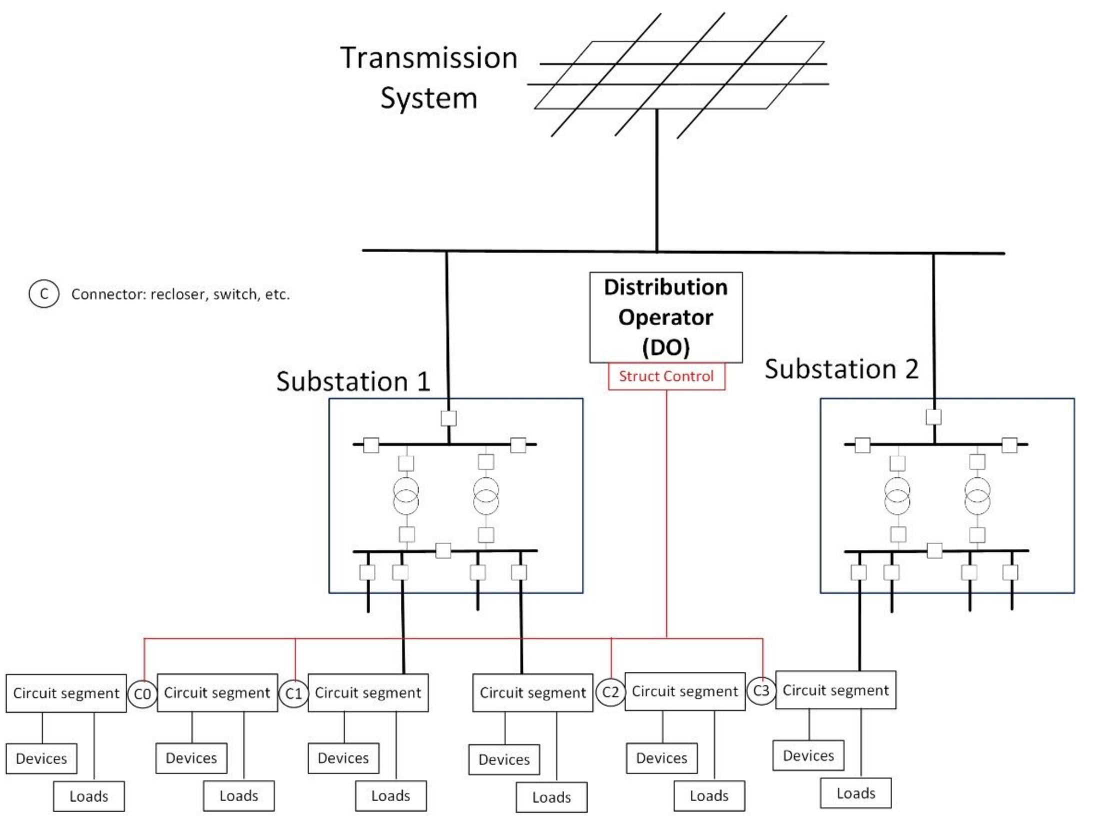

Figure 12 Centralized Grid Structure Control Model

In this model, the system model (circuit topology and parameters) and circuit structure state (connector settings) must reside in a central data store at the operations center. The simultaneous solution for grid structure, power flow, and storage state of charge would be necessary to facilitate operation of grids that may have multiple proposed virtual power flows (to accommodate various energy transactions) that must be resolved into a single actual power flow solution. Centralized structure control can be combined with both Laminar Networks and LENs, as illustrated in Figure 13. This results in a control strcture that is independent of the coordination structure and operated in parallel, with convergence at the DO Operations Center level. In effect, the connector control would act as if it exists at the Laminar 2nd tier level.

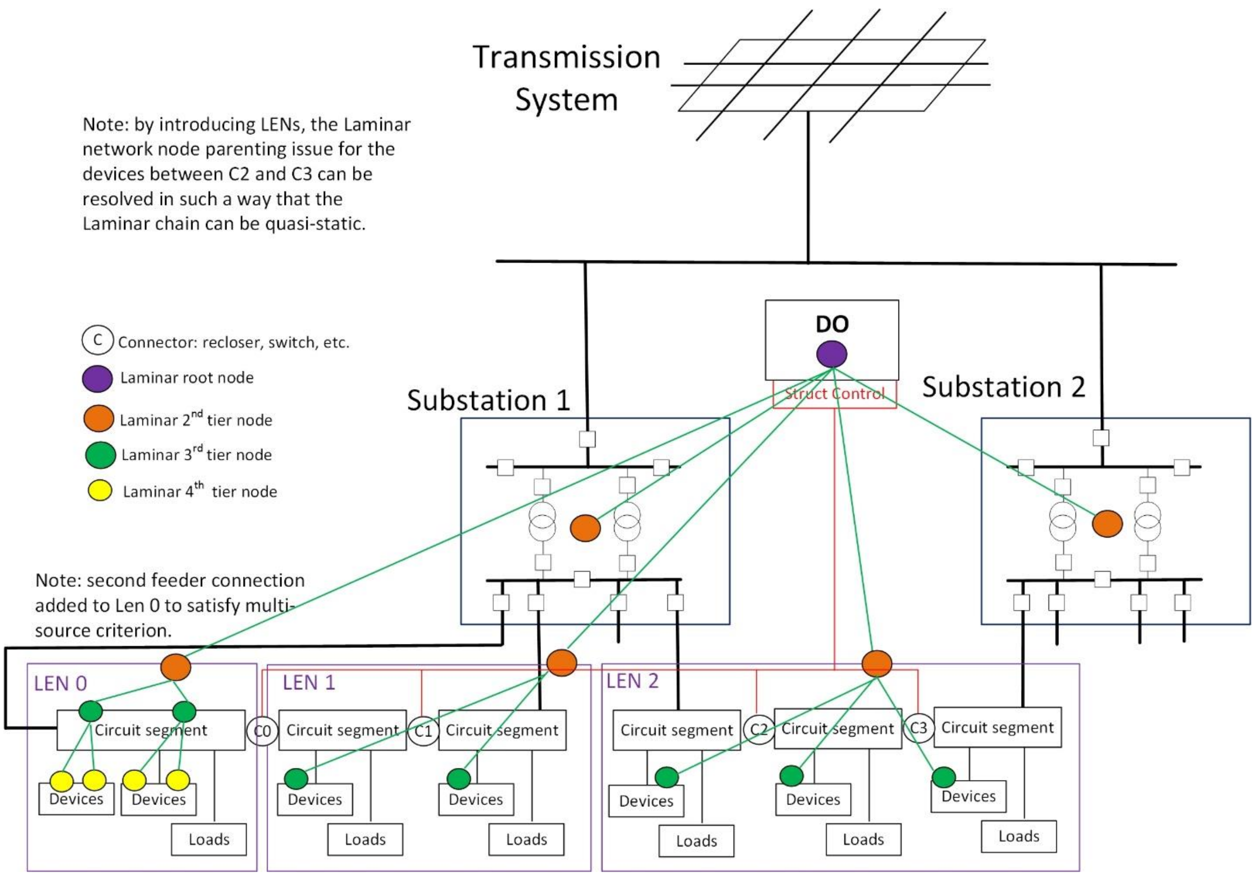

Figure 13 Variable Grid Structure with LENs, Laminar Coordination, and Separate Structure Control

Another approach for grid structure control is to combine this with the general coordination problem. In that case the Coordination Network would be used and the connectors would be included in the Laminar Network. Figure 10 above illustrates the resultant composite structure. In this case the grid structure control is essentially absorbed into the coordination framework, which increases the complexity of the coordination process, but offers the potential for a distributed solution that can operate in partitions if resilience events cause fragmentation of the communication network.

Specification 5 details:

5.1 Control for variable structure must solve simultaneously for power flow and grid structure, taking into account thermal, voltage, stability, and protection constraints.

5.2 If LENs are to be operated in islanded modes, then each must also be capable of solving any internal structure control problems, should they exist.

5.3 For the grid structure control problem to be solved in a centralized fashion, as is done in the BPS, grid model (topology and model parameter) information must be available at the central control point.

5.4 For distributed structure control, grid model (topology and model parameters) information must flow in a horizontal (segment to segment and LEN to LEN) fashion but must be able to flow through to distant segments or LENs as well as to adjacent segments or LENs. Use the communications layer underlying the variable grid structure (Specification 1.3) to avoid multi-hop latency issues.

5.4 Each LEN has a local control/intelligence capability that supports local load, energy resource, and grid operational management.

Specification 6: 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 Variable Structure Data Architectures (VSDA), the design-time data models for particular instantiations of the data processed in the grid are to be established during the design of the particular instantiation of the grid. (Those detailed designs start with a conceptual data model focusing on build entities and their relationships, evolving into concrete data models for data communication and management in the form of data stores, and eventually to physical data models.) Traditional (BAU or as-built) data flow for structure management along with power flow control is shown in Figure 14.

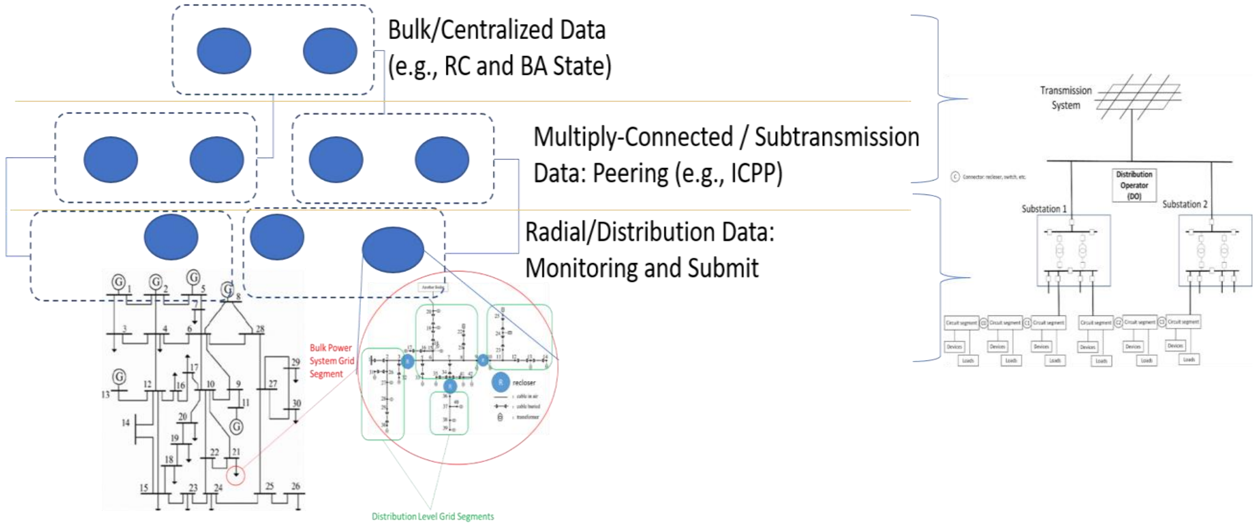

Figure 14 Data Exchange for Traditional (Today's As-Is) Structures

To enable the VSDA construction as described in this specification, the data flow architectures must map to the laminar structures described in Specification 3 (Coordination of Variable Structure Distribution Grids). We illustrate this by showing the structural mapping of the data layers to a laminar layering shown in Figure 15. The important data component that is new to the operation of VSDA is a view of limited (**core)** data elements that are required for operational autonomy of the grid sub-structure irrespective of the "different" structures they are configured into, and additional (**peering-enhanced**) data elements that support the variable structure flexibility. We must assume here that the structural components of the grid that are subject to variable structure will be essentially defined in advance. This does not limit the degree of flexibility, but it does limit the scope of system configurations permitted. This is required because the physical operations of the grid require power flow balance, resiliency, and safety assurances that cannot be met with arbitrary structural changes.

The mode of allowing variable structure in the grid which is also amenable to correct cyber-physical control is discussed in Specification 5 (Control of Variable Structure). The problem of controlling a dynamic reconfigurable grid (i.e., a variable structure enabled environment) depends on the technology in use and its implementation, but the data flow requirements are supported by the two data architecture components of (i) core data elements that do not need to be exchanged between components of the variable structure, and (ii) peering-enhanced data elements that communicate control and coordination information for new structures that are permitted in the grid.

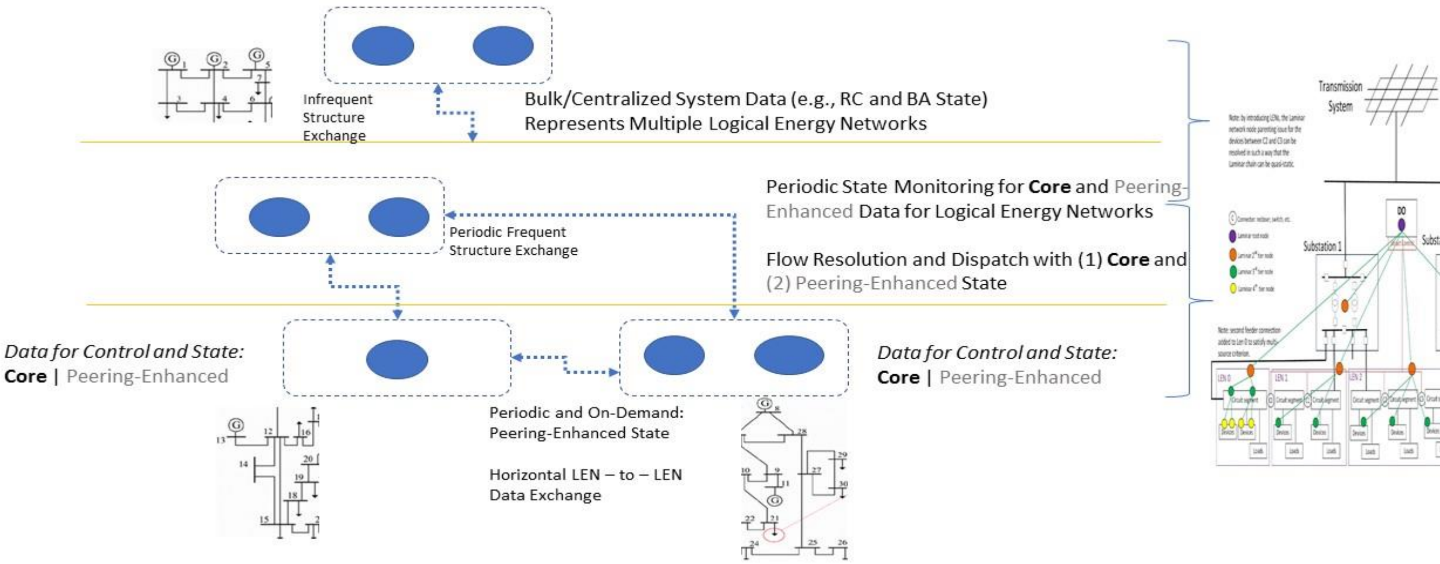

Figure 15 Data Exchange for Variable Structure Grid Architectures

Figure 15 shows how the as-is rigid structures evolve to map to the LEN and laminar constituents (shown in the right). Architectural components must have data for core operations when they are a part of a variable structure configuration. In addition, they must exchange additional information when they dynamically form a linked circuit structure. The exchange of the state information is periodic with the frequency determined by the control and coordination logic.

Figure 16 illustrates the data flows involved in the formation of these substructures.

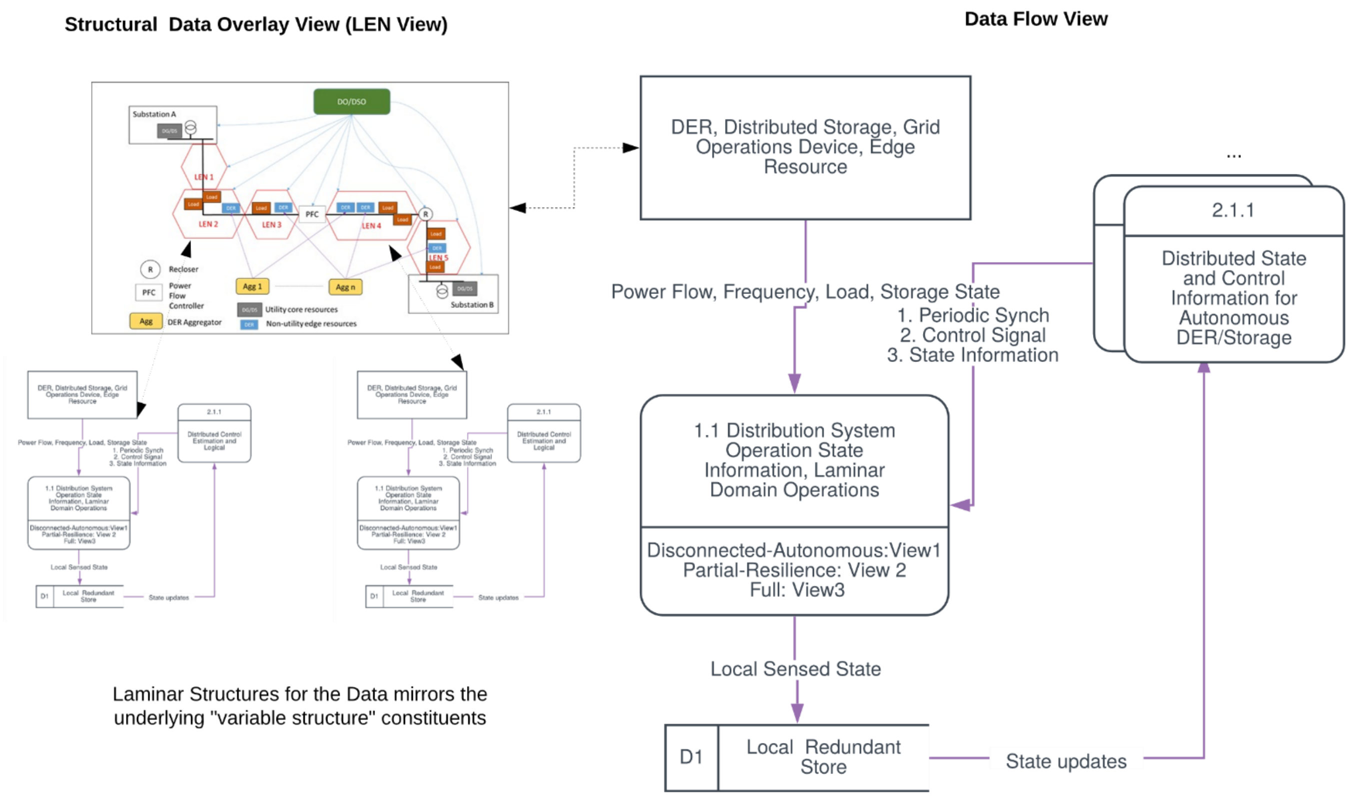

Figure 16 Data Flows for Distributed Variable and Multi-Structure (e.g., High-DER) Deployments

The structural correspondence of multiple (potentially autonomous) DERs and Storage systems in LENs that constitute the building blocks of the variable structure representations is shown on the left of Figure 16. Data is stored locally to enable the laminar domain operations as described in the Specification 2 (Distributed Sensing and Communication) and Specification 4 (Virtualization of Variable Structure Distribution Grids). 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 module 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.

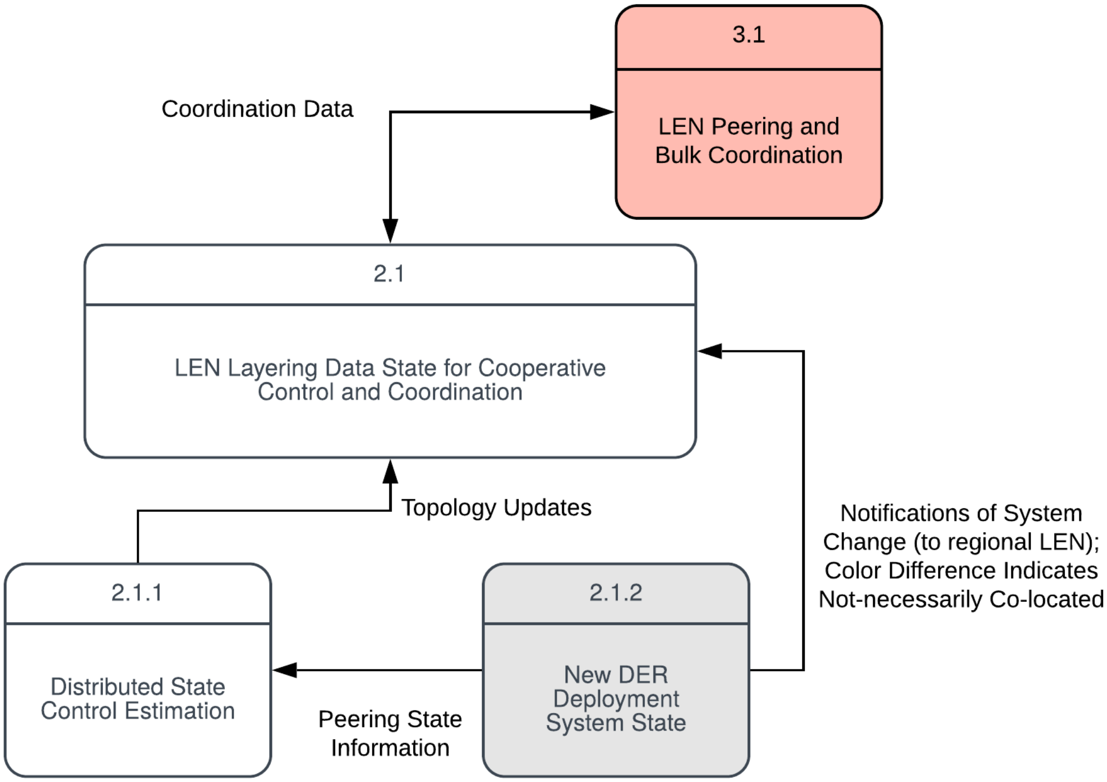

Figure 17 Data Flow Needs to Enable Coordination and Collaboration across Variable Structure Components

Figure 17 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 illustrated in Figure 16 and these data elements (represented in Figure 17 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 variable structure.

To address this issue, data processes must be developed to incorporate system state change (Shown in 2.1.2) and these notifications must 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 that 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 6 details:

6.1 Edge devices, microgrids, DERs must retain data within an accepted resilience time window.
6.2 The locus of laminar coordination must store the data using established state information gathering and control methods.
6.3 Variable structure constituent components (and sub systems/structures) must be able to operate in the different modes into which they will be configured.
6.4 This requires them to have a core set of data elements for state and control, and a peering-enhanced set of state and information they exchange in different structural configurations.
6.5 The data service interface must be addressable in a uniform manner. In this regard, the location for a data service for state information retrieval must be available at the Utility, DSO, and LEN levels. (This must be implemented similar to DNS lookup and addressable IP ports.)
6.6 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.)
6.7 A Data flow service for eventual consistency must be implemented. (The needs for this are defined by the control coordination method implemented based on the technology in use.)
6.8 Control protocols must operate with partial data resident at a LEN.
6.9 Data sources should submit data, and data should be held and made available within required time constants for the correct implementation of distributed control, stress resistant, and strain tolerance algorithms deployed in the resilient grid. Ensure that timing distribution dependencies are explicit.

List of Attached Documents and Reference Papers

Document Name/File Name	Description	Version/Date
Architectural Framework for Variable Structure Grids v0.4.docx	Architectural Framework for Variable Structure Grids	V0.5/24 Sep 2019
NRECA Next Generation Grids.pptx	C Miller Agile/Fractal Grid presentation	March 2017
Overview of the Agile V2.pdf	M. Martin Overview of the Agile, Fractal Grid white paper	V2/May 2017
Var Struct Ref Arch Drawings1.4.vsdx	Visio drawings for the specification	Ver 1.4/Sep 24 2019
CSEE Interconnected Microgrids.pdf	Operation of Networked Microgrids in a Distribution System	December 2015
Problem Domain Reference Model – GMLC1.2.1-v2.pdf	Problem Domain Reference Model white paper	Jan 2019
Entities.Definitions.01.09.2019.xlsx	Entities Definitions	March 2019
CA focused industry structure model ER.vsd	California industry structure model (focus on CA ISO service area):	March 2019
New York: *NY Industry Structure Diagram_v1.2.vsd* and *NY Industry Structure Diagram_v1.2.xlsx*	NY Industry Structure Diagram	March 2019
ERCOT Industry Structure Diagram_v1.xlsx and ERCOT Market Control_v0.1.vsdx.	ERCOT Industry Structure Diagram and Market Control Process Diagram	March 2019
Pacific Northwest: PNW Industry Structure Diagram_v1.xlsx & PNW Industry Structure Diagram_v1.vsdx	PNW Industry Structure Diagram	March 2019
Grid Architecture Component Class Specification – Microgrid v0.1.docx	Grid Architecture Component Class Specification Microgrid	Feb 2019
Grid Architecture Component Class Specification – Power Flow Controller.docx	Grid Architecture Component Class Specification Power Flow Controller	July 2018
Grid Architecture Component Class Specification – Digital Communication Network.docx	Grid Architecture Component Class Specification Digital Communication Network	Sep 2017

Version History

Action	Date	Description	Author(s)
Created	8/21/2019	Originated as the 1.2.1 variable structure architecture specification top level document	GMLC 1.2.1 team
Added data arch section	9/6/2019	Added the data architecture section	Arjun Shankar
Edits	9/24/2019	Editing pass for the final document	J Taft

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