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Comparative Architecture Analysis: Using Laminar Structure to Unify Multiple Grid Architectures

November 2016

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U.S. DEPARTMENT OF
ENERGY

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1.0   Introduction

A great many architectures for various aspects of electric grids have been proposed over recent years and new ones continue to be suggested. Generally speaking, there is no means except ad hoc analysis by which one can reduce these architectures to some common basis, or extract common elements. This leads to confusion in choosing an architecture for implementation, as well as making it difficult to identify core product or platform opportunities with sufficient potential markets to encourage vendors to provide or develop them.

The discipline of Grid Architecture as defined for the US Department of Energy (DOE) in 2014[1] has multiple purposes. Among them are two that are relevant here:

- Providing rigorous bases for architectural structures

- Identifying common aspects of apparently divergent architectural structures

For the first of these, mathematical methods are applied where possible to provide the rigorous basis for structure. For the second, mapping of architectural structures to a canonical structure puts apparently disparate architectures onto a common basis. In the best case, these two methods coincide.
In this paper, Laminar Coordination structure serves as the rigorously defined common basis for analysis of several real and proposed grid architectures.

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[1] JD Taft and A Becker-Dippmann, "Grid Architecture, " January 2015, available online: http://gridarchitecture.pnnl.gov/media/white-papers/Grid%20Architecture%20%20-%20DOE%20QER.pdf

2.0   Laminar Coordination Framework

Laminar Coordination Frameworks were developed using the mathematics of network utility maximization via layered decomposition.[2] This method has been used for a variety purposes, including communication network management,[3] formulation and solution of problems involving control of Distributed Energy Resources (DER),[4] and coordination of autonomous elements in distributed control systems.[5] In the work on Grid Architecture done for DOE in 2015, layered decomposition was used to develop a coordination framework for distributed control and coordination of grid elements and DER in a highly distributed manner, including mixed control and transactive (market-like) elements.[6]

The basis for Laminar Coordination is the formulation of an optimization problem with coupled constraints. A standard means of solution is layered decomposition, as illustrated in Figure 1 below.
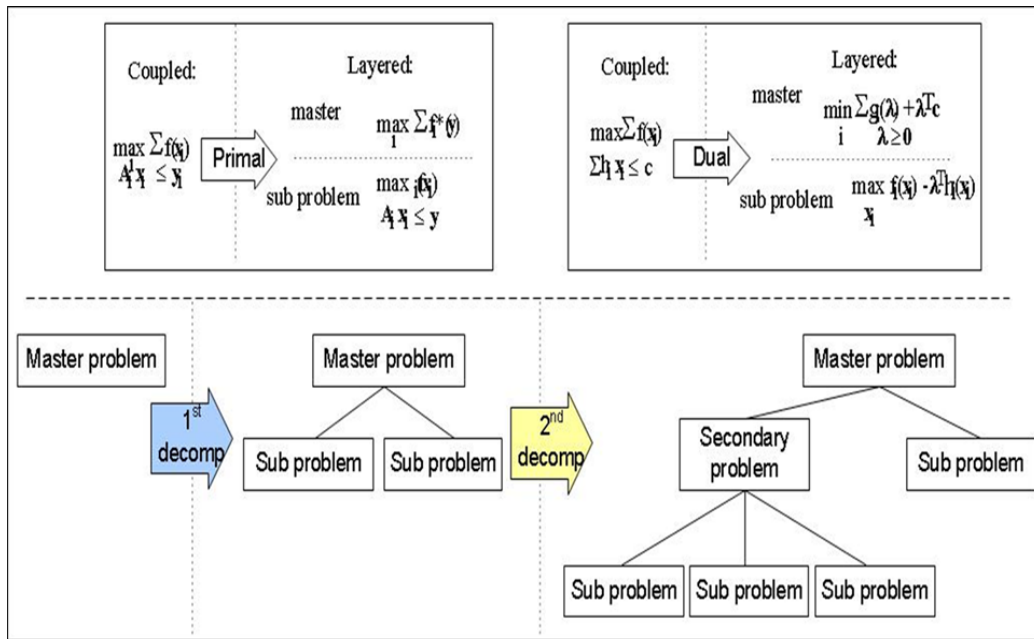

Figure 1. Layered Decomposition

In the theory of distributed control, a key issue is the mechanism that keeps decentralized and autonomous elements focused on solving a common problem. One class of methods involves goal modification; the other, of interest here, is the use of structural methods. The second approach is of interest because the goal was to extract essential structure from the mathematics, so as to have a basis for

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[2]Mung Chiang, et. al., "Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures," <u>Proceedings of the IEEE</u>, Vol. 95, No.1, January 2007.

[3] Daniel P. Palomar and Mung Chiang, "Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications," <u>IEEE Transactions on Automatic Control</u>, Vol. 52, No. 12, December 2007.

[4] Na Li, Lijun Chen, and Steven Low, "Optimal Demand Response Based on Utility Maximization in Power Networks," available online at: <u>http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6039082&tag=1</u>

[5] M.D. Mesarovic, et. al., "Two Coordination Principles and Their Application in Large Scale Control Systems," <u>Automatica</u>, March, 1970, Pergamon Press Inc., Elmsford, New York.

[6] JD Taft, "Architectural Basis for Highly Distributed Transactive Power Grids: Frameworks, Networks, and Grid Codes," June 2016, available online: <u>http://gridarchitecture.pnnl.gov/media/advanced/Architectural%20Basis%20for%20Highly%20Distributed%20Transactive%20Power%20Grids_final.pdf</u>

understanding the properties inherent in the structure. When the structure *induced by the mathematics* of layered decomposition is extracted and examined, a multi-scale form emerges that uses a stacked hub and spoke arrangement to provide pathways for coordination signals (see Figure 2).
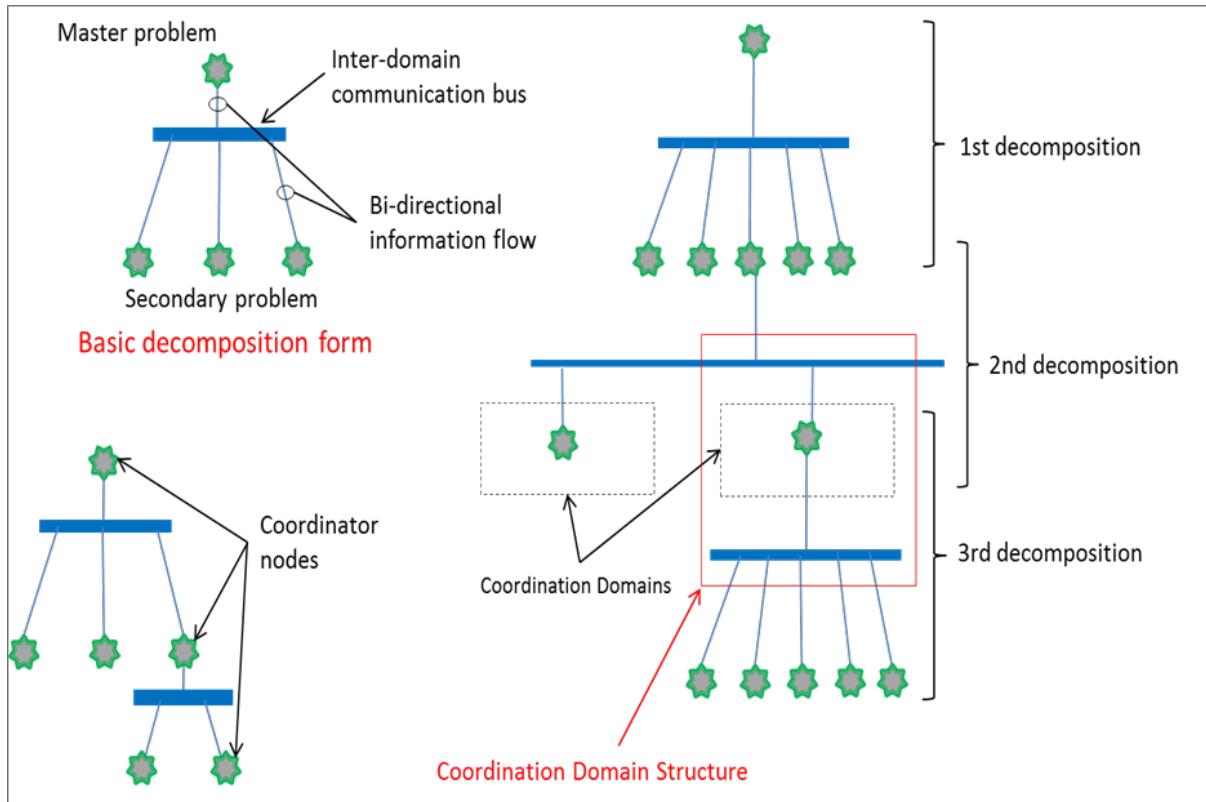

Figure 2. Stacked Hub and Spoke Structure and Coordination Domains

In addition to the layered hub and spoke structure, a repetitive cellular form (the coordination domain) also emerges that becomes a general building block for composing arbitrarily large systems as needed to match underlying infrastructure, namely the electric grid in its various topologies.

Coordinator nodes provide the distributed processing that does the work of aligning local elements by exchanging coordination signals in well-defined patterns. The coordinator nodes themselves have core functionality defined by the mathematics, but serve additional purposes as well. Figure 3 below shows the general form of a laminar coordinator node.
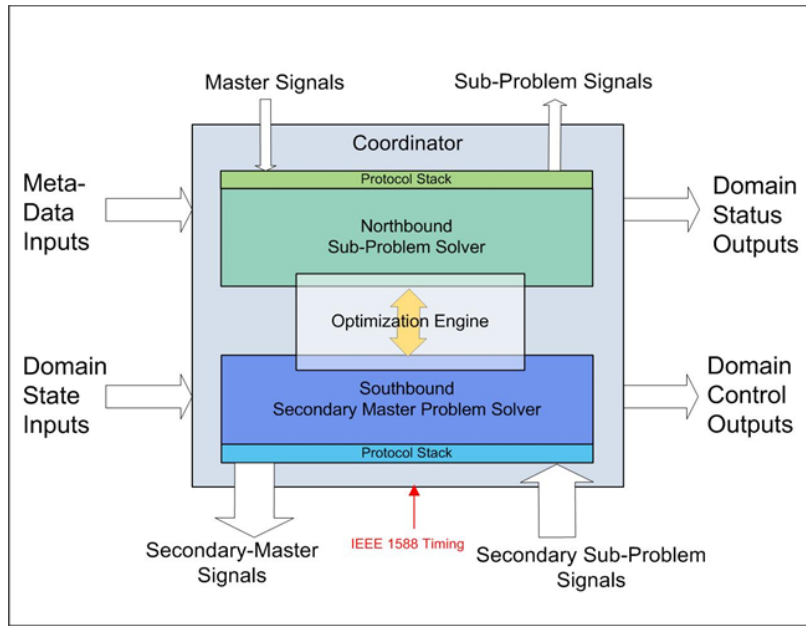
Figure 3. Coordination Node

Combining the coordinator node with its domain provides a view of local (intra-domain) structure and how coordination flows among domains as illustrated in Figure 4.
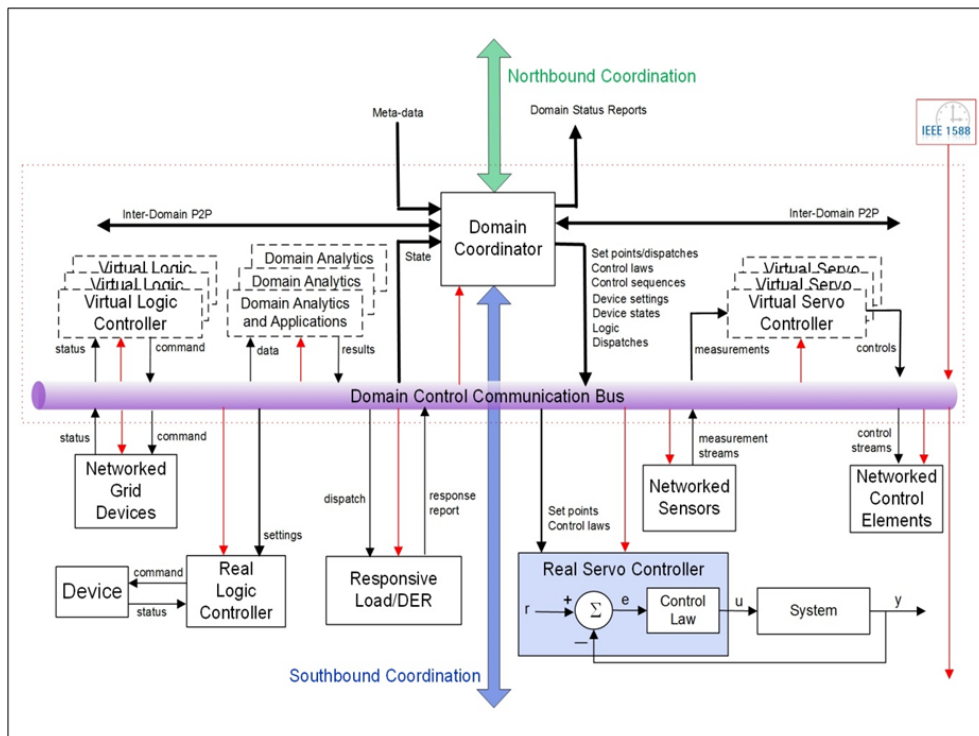

Figure 4. Local Coordination Domain and Coordination Flow

The Laminar Coordination Framework can be used to structure the information flows for a decentralized system or can be used to solve an actual distributed control problem by solving an optimization problem related to the underlying physical system. The mathematics of layered decomposition provides insight

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into the convergence and therefore computational scaling properties of such structures and the Laminar topology can be used to understand communication scaling and cyber security vulnerability issues. Finally, the Laminar structure defines essential aspects of the necessary communication networks. Some key properties of Laminar Coordination Frameworks are:

- Extensibility – the composable nature of laminar coordination domains means that a framework can be made to fit an existing grid structure, can be built out incrementally, and can be extended incrementally when grid structure changes.

- Boundary deference – the decomposition method and composability of coordination domains enables the creation of an interface wherever one is needed to accommodate a system or organizational boundary.

- Local objective support (selfish optimization) – by introducing additional objective terms at any particular coordinator node, local objectives can be integrated into the overall solution. This is a form of goal decomposition.

- Constraint fusion – by adding in constraints as needed at any coordinator node, local constraints can be accommodated in a distributed fashion.

- Scalability – since coordination signals do not need to aggregate up or down the coordination chain, no communication scalability issues arises due to depth of the coordination chain. Layered decomposition can be used to create new layers as needed if the southbound fan-out for any particular node becomes too large, thus providing structural scalability.

- Securability – the inherent form of the coordination framework and consequent coordination signal flows provides a degree of regularity that supports signature and traffic analytic security measures much more so than arbitrary networking for Transactive Energy nodes and other unstructured coordination schemes.

Additional properties have been hypothesized but require additional mathematical development to verify.[7]

In this paper Laminar Coordination Frameworks provide the basis for unifying a number of architectures either in use or proposed for use in electric power systems. This analysis not only unifies these architectures, but points to how some of them could be improved.

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[7] J Taft and P De Martini, "Scalability, Resilience and Complexity Management in Laminar Control of Ultra-Large Scale Systems," available online:
http://gridarchitecture.pnnl.gov/media/advanced/Scalability%20and%20Resilience%20in%20Laminar%20Control%20Networks.pdf

3.0   Unification of Various Grid Architectures

The Laminar Coordination Framework provides a canonical structure onto which many other architectures can be mapped. Doing so shows the common bass for these architectures, and makes it possible to use the properties of Laminar structure to analyze and characterize these architectures as described above.

3.1   Centralized Control Structure

Traditional centralized grid control has a simple hub-and-spoke logical structure and when the communication networks are point-to-point, has the same physical structure as well. In a real grid there may be several of these structures operating in parallel (see Figure 5).
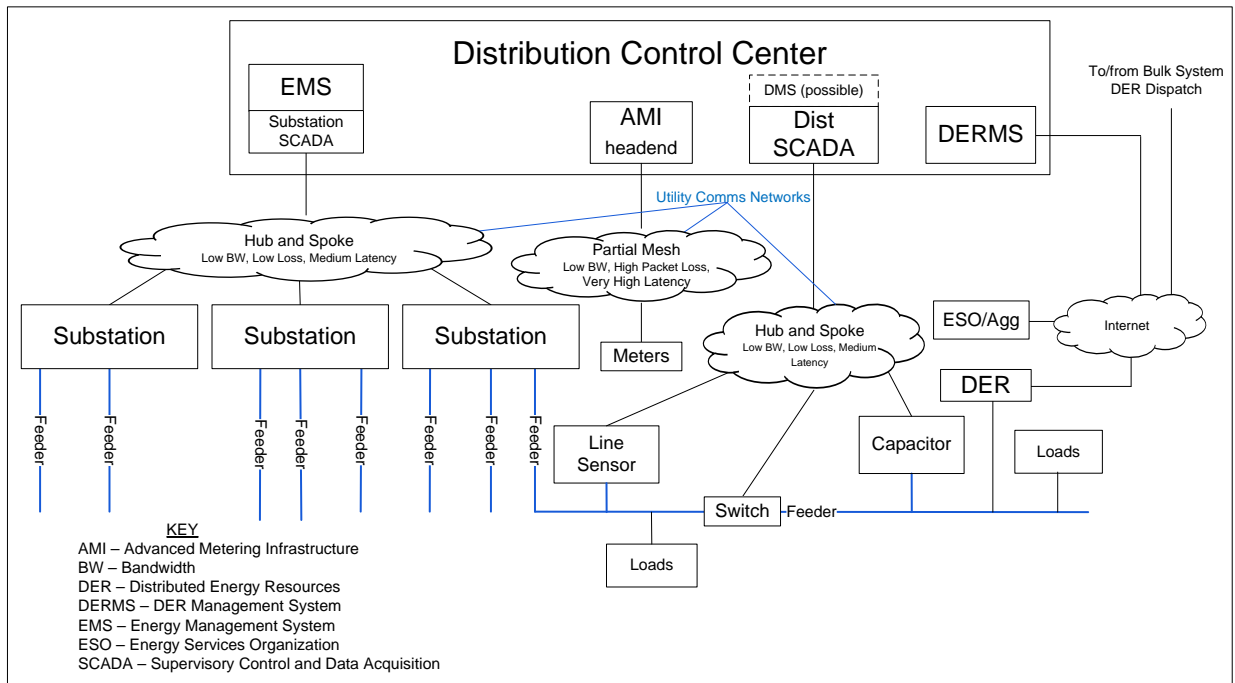

Figure 5. Centralized Controls with Multiple Hub-and-Spoke Control Systems

The centralized grid control structure is a simplified version of the Laminar structure, in that there is only one level of decomposition, and for the typical case where the lower layer nodes have no intelligence, all of the coordination is done at the master (top-level) node. If the field (lower level) nodes were to have local intelligence, then the coordination/control problem could be distributed in congruent to the layered decomposition approach with no other change in structure required. Therefore we may view the conventional centralized control model as a degenerate form of the Laminar Coordination Framework. We may also view the centralized control structure as one where the lower layer of intelligence has been virtualized back into the top level node. In this manner we can analyze the convergence properties of grand central optimization control schemes with the same tools and methods as we use for the distributed structures.

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3.2 OpenFMB and Distributed Intelligence Platform (DIP)

The OpenFMB specification and Distributed Intelligence Platform (DIP) architecture[8] developed by Duke Energy and its Coalition of the Willing is intended to support both centralized and distributed analytics and control arrangements. This means that the communication network for electric distribution systems must provide aggregation paths to the distribution substations as well as access to feeder level processing nodes. Consequently, the underlying communication network must support general local connectivity and local peer-to-peer communication as opposed to the more common hub-and-spoke arrangement of standard distribution SCADA. Figure 6 from the OpenFMB collaboration site illustrates in high level form the structural concept behind this approach. While it is not depicted in quite the same form as the Laminar Coordination Framework diagrams, it is possible to determine the mapping between these two structures.
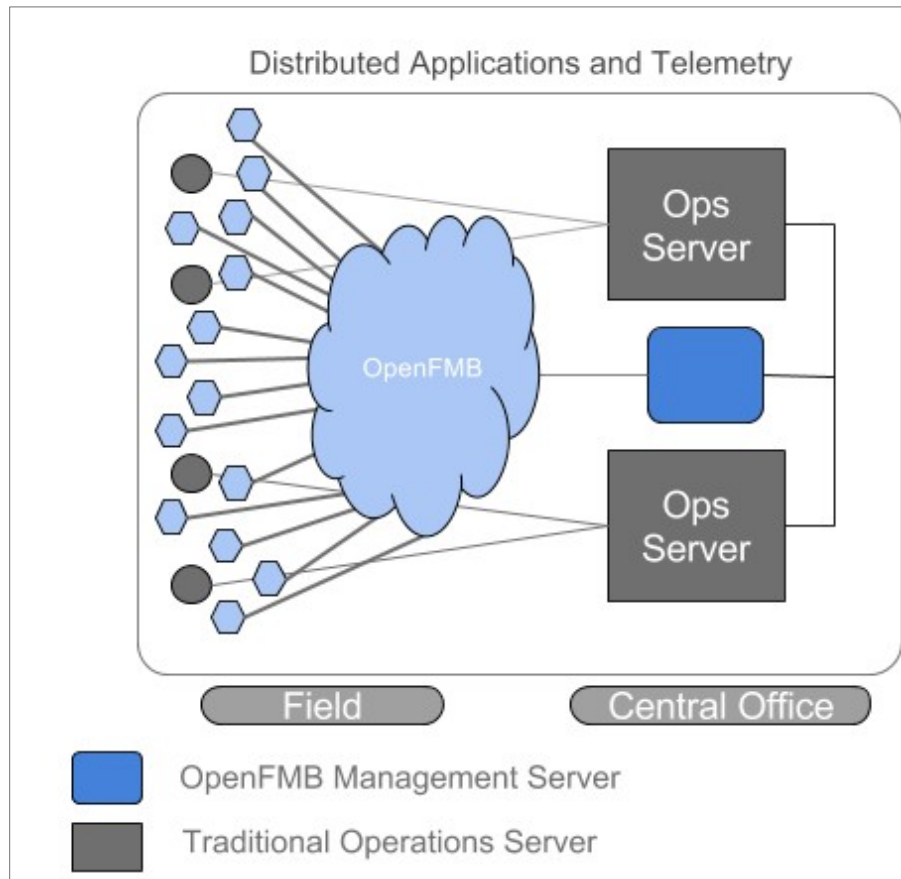

Figure 6. OpenFMB/DIP Structure

Such a mapping reveals that the model of the OpenFMB and its processing nodes are homologous with Laminar structure coordination domains and coordination nodes as shown in Figure 3 and Figure 4 above. The Laminar structure provides an architectural context for the DIP nodes and OpenFMB itself. The DIP/OpenFMB architecture is a proper subset of the Laminar Coordination Framework.

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[8] S Laval and B Godwin, "Duke Energy, Distributed Intelligence Platform (DIP) Reference Architecture, Vol. 1, " available online at www.duke-energy.com/pdfs/dedistributedintelligenceplatformvol01.pdf

3.3 Transactive Energy Systems

Transactive Energy Systems are systems that employ techniques for managing the generation, flow, and consumption of electric power within an electric power system through the use of economic or market based constructs while considering grid reliability constraints.[9] Transactive Energy systems can exist in several forms, but for electric distribution systems and DER, they are envisioned as distributed systems employing a network of transactive "nodes" and intelligent DER endpoints. Several demonstration projects have been built, each with its own design and underlying structure. Recent work has shown how to use the Laminar Coordination Framework as the architectural basis for highly distributed transactive energy systems.[10] Figure 7 below illustrates the application of Laminar Coordination to Transactive Energy Systems, including communication structure.
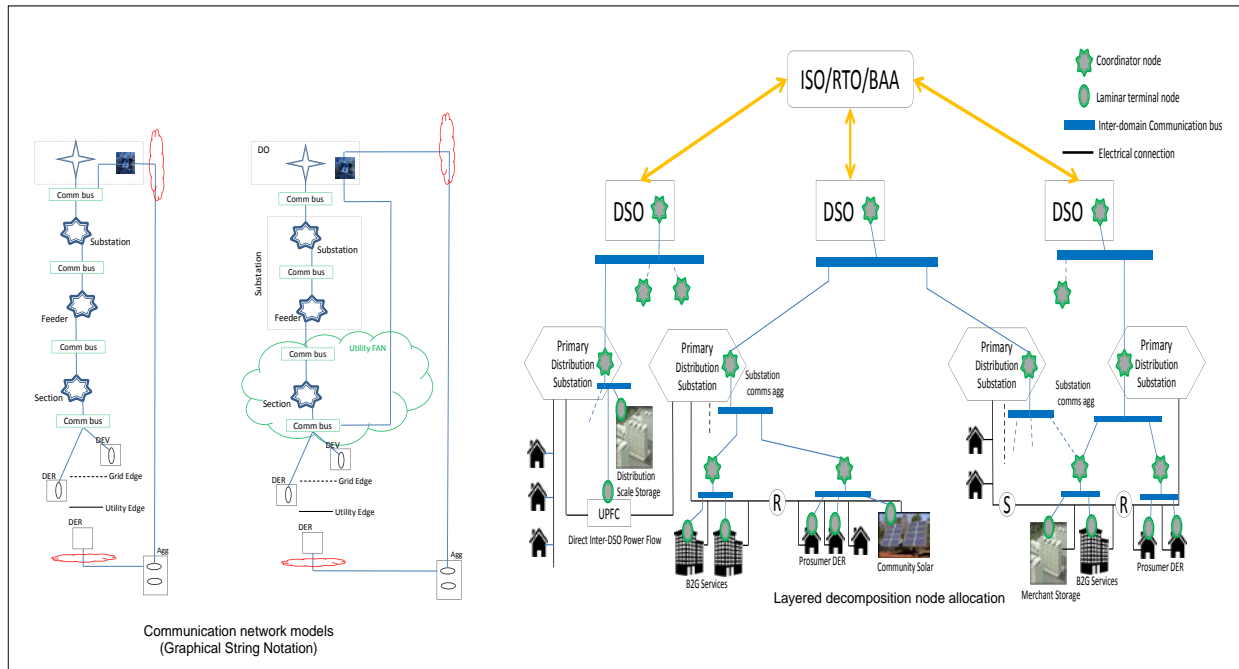

Figure 7. Laminar-Structured Transactive Energy System Architecture

The application of the Laminar framework led to a flexible structure that informs both coordination/control and communication networks for distributed Transactive Energy Systems and provides insight into interoperability requirements. In this case the proposed architecture for Transactive Energy Systems is precisely the Laminar Coordination Framework, by design.

3.4 Distribution System Operator

The concept of Distribution System Operators (DSOs, also known as Distribution Service Platforms or DSPs) has evolved out of two kinds of concerns: the problem of managing high penetration DER for both bulk system and distribution operations while maintaining distribution reliability; and the emerging

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[9] http://www.gridwiseac.org/about/transactive_energy.aspx

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

problem of tier bypass in grid system due to the same cause. The former led to new models for the roles and responsibilities of distribution operators and system operators[11], while the latter led to new views about multi-scale grid coordination and control.[12] The two views have converged, based on separate paths to similar conclusions about the use of layered decomposition.[13] The Laminar Coordination Framework mode is now used for the industry structure component of emerging DSO models, wherein the relationship between distribution and bulk systems, between DSOs and system operators follows the Laminar framework both electrically, and in terms of coordination, dispatch, and control. The approach to DSO models described in the reference is explicitly the Laminar framework, as applied to industry structure. It connects with the use of Laminar structure for control and coordination at multiple scales.

3.5   Fractalgrid/Agile Fractal Grid

These are two closely related concepts for how to connect multiple microgrids into large more or less cellular systems. The term fractal is used to imply multi-scale self similarity although it might be better characterized as multi-scale cellular automata with a degree of self-affinity. Nevertheless, each has some notion of multi-scale coordination, although in both cases it seems to be essentially ad hoc in nature, not based on a rigorous foundation. Both have concepts of peer-peer interaction and in the case of agile fractal grids, there is recognition of a need for multi-scale coordination. In the case of Fractalgrid, there is at least one implementation that uses a two level structure.[14] It is worth noting the similarity to Balancing Authority Areas at the bulk energy system level.

The agile fractal grid concept is described as follows:[15]

> *Agile control rests on the rapid and accurate collection and sharing of information at all levels of grid operation, and the integration of advanced analytics to manage the data and assess control options. The foundations are a communications network that you can trust (the Industrial internet), and a fractal architecture on which each fragment of the grid operates like a complete grid, using an information and control paradigm that can be shared with other fragments to allow coordinated operation, islanding, and reintegration.*

This implies both electrical structure and control/coordination structure. The "grid fragments" map to coordination domains in the Laminar model.

In addition, the following have been listed as fractal grid principles:[16]

1.   All segments of the grid operate with the same information and control model –regardless of scale

2.   Every segment of the grid has a decision making capability

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[11] L Kristov and P De Martini, "21st Century Electric Distribution System Operations," May 2014, available online: http://gridarchitecture.pnnl.gov/media/white-papers/21st%20C%20Electric%20System%20Operations%20%20050714.pdf

[12] J Taft and P De Martini, "A Strategic Framework for Integrating Advanced Grid Functionality,: June 2014, available online: http://gridarchitecture.pnnl.gov/media/advanced/ULS%20Grid%20Control%20v3.pdf

[13] P De Martini and L Kristov, "Distribution Systems in High Distributed Energy Resources Future," https://emp.lbl.gov/sites/all/files/FEUR_2%20distribution%20systems%2020151023_1.pdf

[14] A Villanueva, "Camp Pendleton Fractal Grid Demonstration," California Energy Commission, December 2014, available online: http://www.energy.ca.gov/2016publications/CEC-500-2016-013/CEC-500-2016-013.pdf

[15] http://smartamerica.org/teams/the-agile-fractal-grid/

[16] C Miller, "The future grid Engineering Dreams," available online: http://e2rg.com/workshops/Plenary_Craig-Miller.pdf

3. The means for exchange of peer-to-peer information are clearly defined in standards

4. The rules for when to divide and when to combine are clearly defined

While the actual coordination and control structure for agile fractal grids is not detailed, it has been described as a "multi-scale" in nature. Note that the Laminar Coordination Framework provides actual mechanisms for the four principles listed above where segments are coordination domains. In fact, one of the presentations on agile fractal grid makes use of a Laminar Coordination Framework diagram.[17] The Laminar coordination structure could and should be adopted for this purpose in the agile fractal grid paradigm. This would address the apparent gap in how to define a rigorous control schema for such grids.

3.6 Grids with Intelligent Periphery (GRIP)

GRIP is a concept developed by researchers at UC Berkeley, CalTech, WSU, U Fla, U Hawaii, and CIEE.[18] It posits a grid structure that clusters resources, with clusters being managed by intelligent "cluster coordinators," while groups of clusters are managed by a "grid administrator" that interfaces with a system operator such as an ISO. Figure 8 below, which is taken from the paper cited in the footnote, illustrates the hierarchical nature of the proposed structure. The referenced paper implicitly posits some form of coordination but does not explain how this works. Clusters can be mapped to Laminar coordination domains and both cluster coordinators and grid administrators can be mapped to Laminar coordinator nodes at different hierarchical levels.

The description is also roughly consistent with the DSO concept and the extension of a coordination framework in a layered fashion down to the device level but is apparently entirely ad hoc in form.
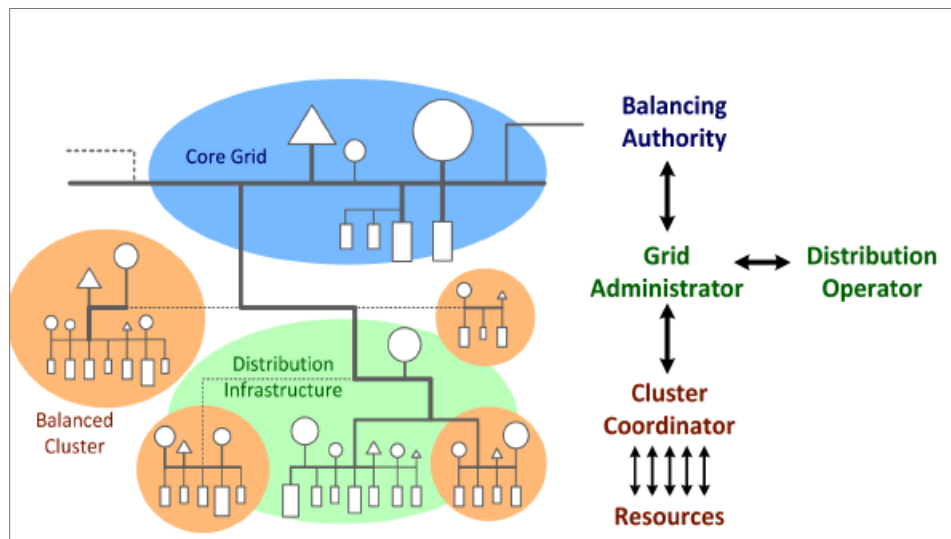

Figure 8. Basic Form for GRIP Architecture

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[17] C Speicher and J Reynolds, "The Agile Fractal Grid," Security Fabric Alliance and The Industrial Internet Consortium July 2014, available online: http://www.slideshare.net/ChuckSpeicher/agile-fractal-grid-71114

[18] D Bakken, et.al., "GRIP – Grids with Intelligent Periphery: Control Architectures for Grid2050," available online: http://smart.caltech.edu/papers/gripgrids.pdf

3.7 Scalable and Flat Controls for Reliable Power Grid Operation

A multi-university group of researchers has suggested that grid control could be accomplished via a structure they refer to as "scalable and flat."[19] Figure 9 below shows the essential structure for control and coordination described in the cited reference.
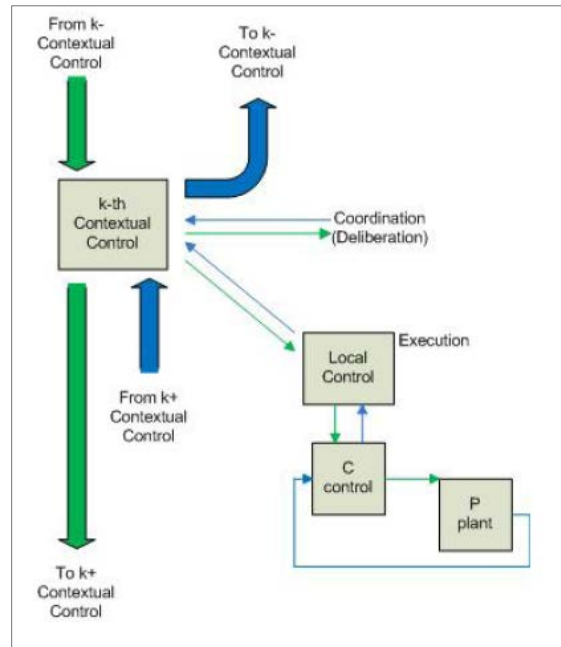

Figure 9. "Scalable and Flat" Control Structure

This structure uses the concept of local control supervised by larger scale "contextual control" that selects from among system-level control goals. In this model, local controls map to Laminar coordination domains, and the contextual control chain maps to a chain of coordinator nodes. The approach is limited to two levels at each scale, so the structure has some constraints that are intended to keep the control "flat"; these constraints do not exist in the Laminar approach since there is no intent to limit the depth of the layered decomposition.

The "scalable and flat" structure is a delimited version of the laminar structure that employs a supervisor/slave approach to two-level coordination but does not describe how interconnected contextual controls perform coordination. This architecture is only a partial match to the Laminar framework.

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[19] K Tomosovic, et.al., "Scalable and Flat Control for Reliable Power Operation with High Renewable Penetration," Stanford University Global Climate and Energy Project, February 2010, available online: https://gcep.stanford.edu/pdfs/factsheets/Tomsovic_electric_09_revised_category.pdf

4.0   Final Comments

The Laminar Coordination Framework is derived from the mathematics of layered decomposition solutions to optimization problems involving coupled constraints. The mathematics can be said to induce a structure, which is the architectural framework for Laminar Coordination. In the context of electric power grids, this framework can be used to develop actual designs, but can also be used as a canonical basis upon which to perform analyses of existing and proposed grid architectures with respect to control, coordination, and communications as well as physical (circuit) structure.

Analysis of grid architectures by mapping to Laminar Coordination Frameworks shows commonalities across several apparently disparate approaches including traditional centralized control, OpenFMB, fractal grids, scalable and flat controls for grids, and Distribution System Operator models. It also facilitates making conceptual connections between structures used at different levels in the grid (e.g. the connection between Balancing Authority Areas and fractal grids). The ability to perform this type of structural analysis is missing from approaches to comparing grid architectures, such as SGAM.

Comparative architecture analysis is important for grid modernization decision makers and stakeholders because architecture represents the earliest and highest level design decisions for complex systems and set the essential limits on what systems (in this case power grids) can and cannot do. This analysis provides a means to understand what on the surface may appear to be very different approaches to grid modernization.

- Regulators can use it to understand modernization filings from utilities

- Utilities can use it to select from among architectural alternatives

- Product developers can use it to identify and design products and platforms useful across multiple markets (utilities)

Comparative architecture analysis using a framework with a rigorous basis should be a standard tool for architecture development and evaluation.