



Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Architectural Basis for Highly Distributed Transactive Power Grids: Frameworks, Networks, and Grid Codes

June 2016

JD Taft

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes **any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.** Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST NATIONAL LABORATORY

operated by

BATTELLE

for the

UNITED STATES DEPARTMENT OF ENERGY

under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <<http://www.ntis.gov/about/form.aspx>>
Online ordering: <http://www.ntis.gov>



This document was printed on recycled paper.

(8/2010)

Architectural Basis for Highly Distributed Transactive Power Grids: Frameworks, Networks, and Grid Codes

JD Taft

June 2016

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

Simple Transactive Energy Systems have been built using ad hoc approaches to the placement and interconnection of the transactive nodes but engineering principles or design guidelines for building such systems have been lacking. Consequently, the proliferation of transactive Distributed Energy Resources (DERs) and transactive building-to-grid services has been hampered and the development of interoperability standards has been slow.

In order to realize the full potential for extracting the latent capacity and performance available in distribution systems with DER on a real time basis, transactive elements must be distributed throughout the distribution grid to take account of local conditions with sufficient granularity. We may state a new architectural thesis for future grids this way: *given highly volatile and dispersed resources and physical constraints across the grid, provide a unified multi-tier coordination schema that simultaneously optimizes operation across all parts of the power delivery system, from the markets, balancing, planning, and operational levels to the transactive and prosumer levels.*

This paper provides an architectural framework for highly distributed Transactive Energy grids. The framework guides the engineering of transactive distribution systems, informs the necessary interoperability standards, and fills in the gap in the ability of electric distribution utilities to write the Grid Codes that define how prosumer and third party devices plug into such a grid. This architecture resolves a major hurdle to Transactive Grid deployment.

Contents

Executive Summary	iii
1.0 Background and Key Issues	1
2.0 Architectural Approach	1
2.1 Markets and Coordination	3
2.2 Approach	3
3.0 Laminar Coordination Frameworks	4
3.1 Key Properties of Laminar Coordination Frameworks	8
4.0 Laminar Networks	9
5.0 Implications of This Approach	13
6.0 Transactive Distribution Grids and Transactive Grid Codes	13
7.0 The Path Forward	14
8.0 Summary and Conclusions	16
Appendix A – Graphical String Notation	A.1

Figures

Figure 1. Bulk System Transactive Operational Model.....	2
Figure 2. DSO-based System Model.....	2
Figure 3. Layered Decomposition Process	4
Figure 4. Underlying Layered Decomposition Structures	5
Figure 5. General Coordination Domain Internal Structure (Feeder Section Level).....	6
Figure 6. Coordinator Node Detail	7
Figure 7. Partial Coordination Framework	7
Figure 8. Mapping of Laminar Framework to Grid Structure	8
Figure 9. Basic Network	10
Figure 10. ISO Market Network Mode.....	10
Figure 11. Two Market Network Model.....	10
Figure 12. Laminar Networks with Granular Grid Penetration	11
Figure 13. Improved Granular Laminar Networks	12
Figure 14. Transactive Grid Code Stack and Relation to Laminar Architecture	14
Figure 15. Laminar Architecture Impact Flow	15
A.1 Utility Diagram with Laminar Coordination	A.1
A.2 Extraction of a Graphic String Model.....	A.2
A.3 Example with Internet and Utility Wireless Network.....	A.3

1.0 Background and Key Issues

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.¹

A highly distributed Transactive Grid is one in which the transactive platform itself is distributed throughout the grid rather than existing in a centralized form. This especially applies to the distribution-level market mechanisms, should they exist.

Approaches to building distribution level Transactive Energy systems have had several practical shortcomings to date:

- transactive nodes have been placed and interconnected with no particular underlying structure or engineering principle to guide the design
- there are no means for the local integration of transactive nodes to distribution grid control devices
- there are no well-defined plug-and-play interfaces or connection procedures for non-utility owned devices to connect into distributed transactive nodes

The lack of clarity on how to design and configure transactive grid systems on the one hand, and how to interface non-utility DERs on the other, is a significant impediment to deployment of highly distributed Transactive distribution grids. Utility engineers, system architects, network managers, DER device vendors, and system integrators have had to sort out these issues on an ad hoc basis. Furthermore, lack of structure has left the efforts to develop distributed Transactive Energy systems without a rigorous context in which to define and develop interoperability standards and interconnection specifications. Consequently, there is no unified standard way for utilities to specify transactive interconnection in a manner to which device and system vendors could respond.

The development of an underlying architectural basis for highly distributed Transactive Energy systems will alleviate these problems. In addition to informing system design, it will also enable utility engineers to write distribution level Grid Codes (interconnection specification agreements) that will facilitate DER integration and building-to-grid services.

2.0 Architectural Approach

Transactive Energy Systems constitute a spectrum of mechanisms and processes, integrated across a wide time scale. Where central organized energy and power markets exist today (at the ISOs and RTOs), multiple market-control mechanisms have converged into transactive platforms that are used to manage bulk energy systems. Figure 1 below illustrates a basic bulk energy system model, and points out where combined market-control mechanisms exist (where arrows for both markets and controls meet at a box).

¹ http://www.gridwiseac.org/about/transactive_energy.aspx

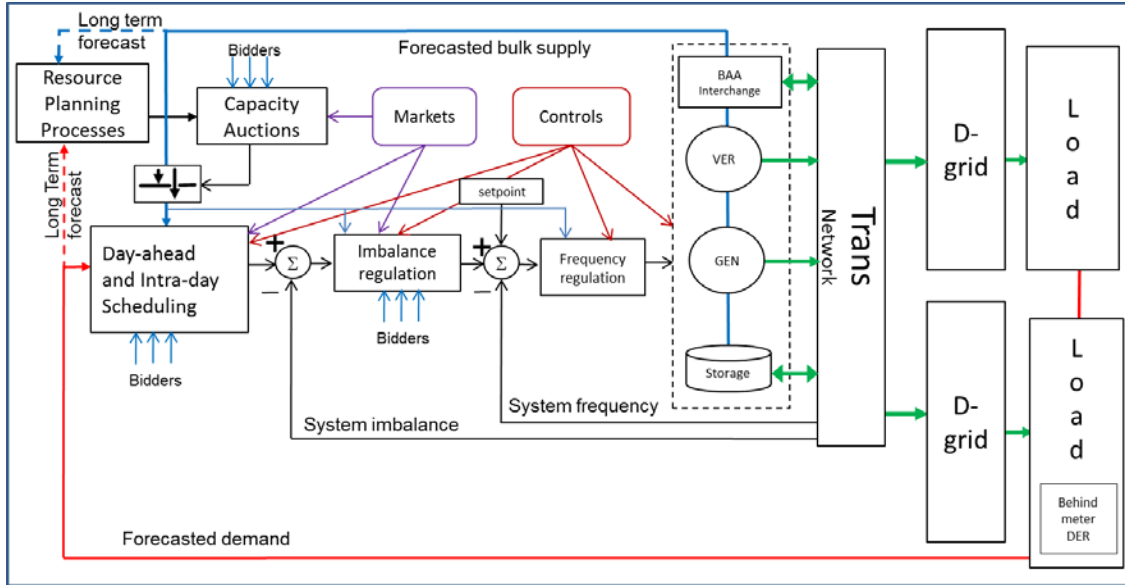


Figure 1. Bulk System Transactive Operational Model

Such a bulk energy system has multiple market-control mechanisms and is in fact transactive. Here we are concerned with the extension of the transactive model to distribution systems as a means to facilitate DER integration, including building-to-grid services integration. In doing so, for conceptual reasons we may invoke the DSO models,² so that distribution systems appear as system nodes to the system operator, with a well-defined transactional interface at the Transmission/Distribution substation or Locational Marginal Pricing (LMP) node, although the use of a DSO is not actually necessary. Consequently, we can focus on the distribution grid, bounded by the Distribution Operator and by the distribution edge-connected devices, and not be concerned with the bulk energy system. Figure 2 illustrates this model.

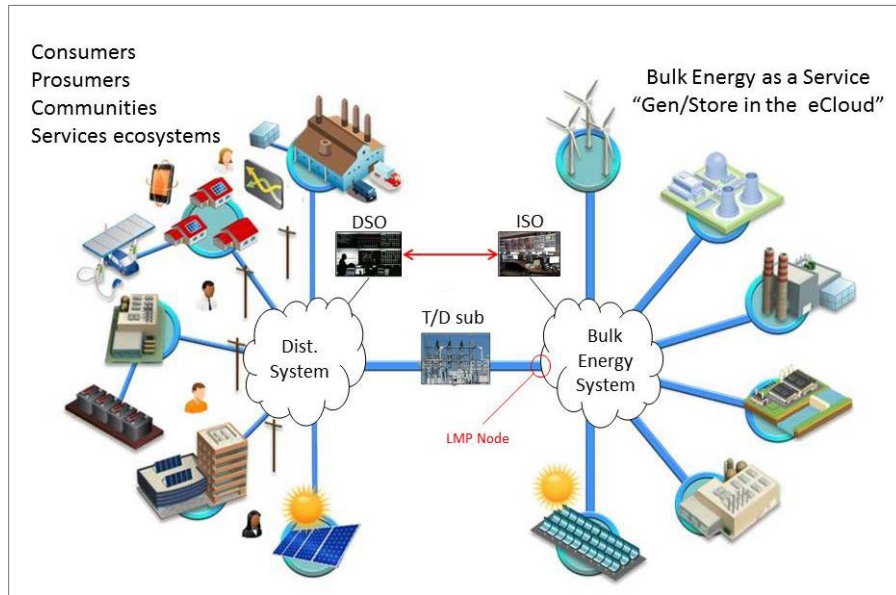


Figure 2. DSO-based System Model

² 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

2.1 Markets and Coordination

Markets are (among other things) mechanisms for providing coordination of large numbers of autonomous elements in a distributed system.³ We usually view markets as means for efficiently allocating resources by enabling competition, but in fact their use in power systems has the effect of *coordinating* system elements such as generators and DER. Markets may not normally be thought of as distributed systems, but they are; confusion comes from referring to markets as “central markets,” but this really refers to the market platform, not the market as a whole. In this work, we are concerned with systems in which *the market platform itself* can be distributed and integrated with control at the electric distribution level.

In the field of distributed and hierarchical control, coordination is the means by which disparate control elements in a distributed control system are kept focused on a common problem to be solved jointly. In the case of electric power systems, coordination structure exists in various forms, some explicit, some implicit or hidden inside other mechanisms or processes, and in some cases, it is actually missing. Coordination, however has become recognized as a key mechanism needed for the comprehensive integration of DER with power grids. We shall use the concept of coordination structure to provide an architectural basis for highly distributed transactive power systems.

Classically, there are two primary methods to accomplish coordination in distributed control systems: goal decomposition and structure decomposition. Goal decomposition is further divided into state adjustment and incentive adjustment methods. While goal decomposition does find use in certain market settings, it does not yield a basis for defining distributed structure. We will revisit goal decomposition briefly later but first we wish to discover structure that can form the basis for an architectural framework. As the name suggests, structure decomposition can yield a framework of the type we seek.

2.2 Approach

We will use the mathematical concept of optimization by layered decomposition⁴ to discover essential structure for a coordination framework. This will lead to an understanding of coordination networks that will form the basis for highly distributed Transactive Energy Systems for electric distribution. Layered decomposition is a well-known avenue to solving certain classes of optimization problems. It has been used as a means for distributed control coordination as far back as the 1970's⁵ and more recently has been used to define communication network architectures⁶ and is now seeing use to formulate grid control problems.^{7, 8} We are not interested here in the formulation and solution of any *particular* control problem by these means; instead we are interested in the class of such problems and what the layered

³ In control engineering and computer science, distributed systems are defined as those where multiple autonomous units cooperate to solve a common problem. This is distinct from decentralized systems where elements are geographically separated. “Distributed” is a process (algorithmic) concept; “decentralized” is a geospatial concept.

⁴ Mung Chiang, et. al., “Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures,” Proceedings of the IEEE, Vol. 95, No.1, January 2007.

⁵ M.D. Mesarovic, et. al., “Two Coordination Principles and Their Application in Large Scale Control Systems,” Automatica, March, 1970, Pergamon Press Inc., Elmsford, New York.

⁶ Daniel P. Palomar and Mung Chiang, “Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications,” IEEE Transactions on Automatic Control, Vol. 52, No. 12, December 2007.

⁷ Na Li, Lijun Chen, and Steven Low, “Optimal Demand Response Based on Utility Maximization in Power Networks,” available online at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6039082&tag=1

⁸ M. Caramanis, et. al., “Co-optimization of Power and Reserves in Dynamic T&D Power Markets With Nondispatchable Renewable Generation and Distributed Energy Resources,” Proceedings of the IEEE, Vol. 104, No. 4, April 2016.

decomposition approach can provide in terms of structure and the essential properties that derive from such structure.

3.0 Laminar Coordination Frameworks

The basic approach to layered decomposition starts with an optimization problem that includes coupled constraints. The problem is solved by decomposing the problem into a master problem and several sub-problems; these are all solved iteratively to decouple constraints until they collectively reach convergence, at which point the solution to the original optimization problem has been produced. The master and sub-problems are coordinated by the exchange of lightweight signals, which we shall designate *coordination signals*. In the basic approach, two decompositions are used: primal decomposition, which yields coordination signals that resemble resource allocations, and dual decomposition, which yields coordination signals that resemble prices. In practice, more sophisticated solution methods are now used, including ADDM⁹ and partial dual decomposition but the basic structure remains. Sub-problems may also be decomposed again, and the decomposition process can be repeated as needed. At each decomposition stage, the sub-problems become simpler, and therefore involve less computation than the layer above would, if solved directly. Figure 3 below outlines the basic process.

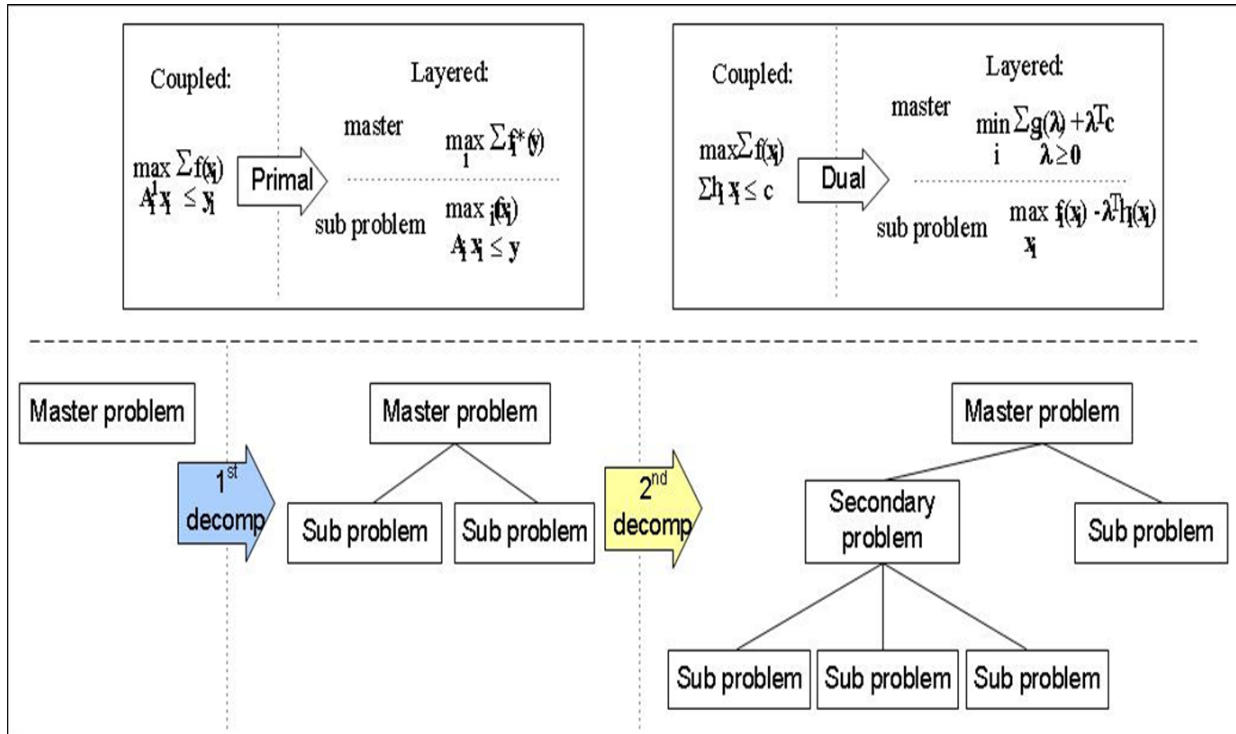


Figure 3. Layered Decomposition Process

Starting from this model, we consider that basic structures implied by the mathematics. Figure 4 shows these structures.

⁹ Alternating Direction Method of Multipliers – a numerical optimization solution technique

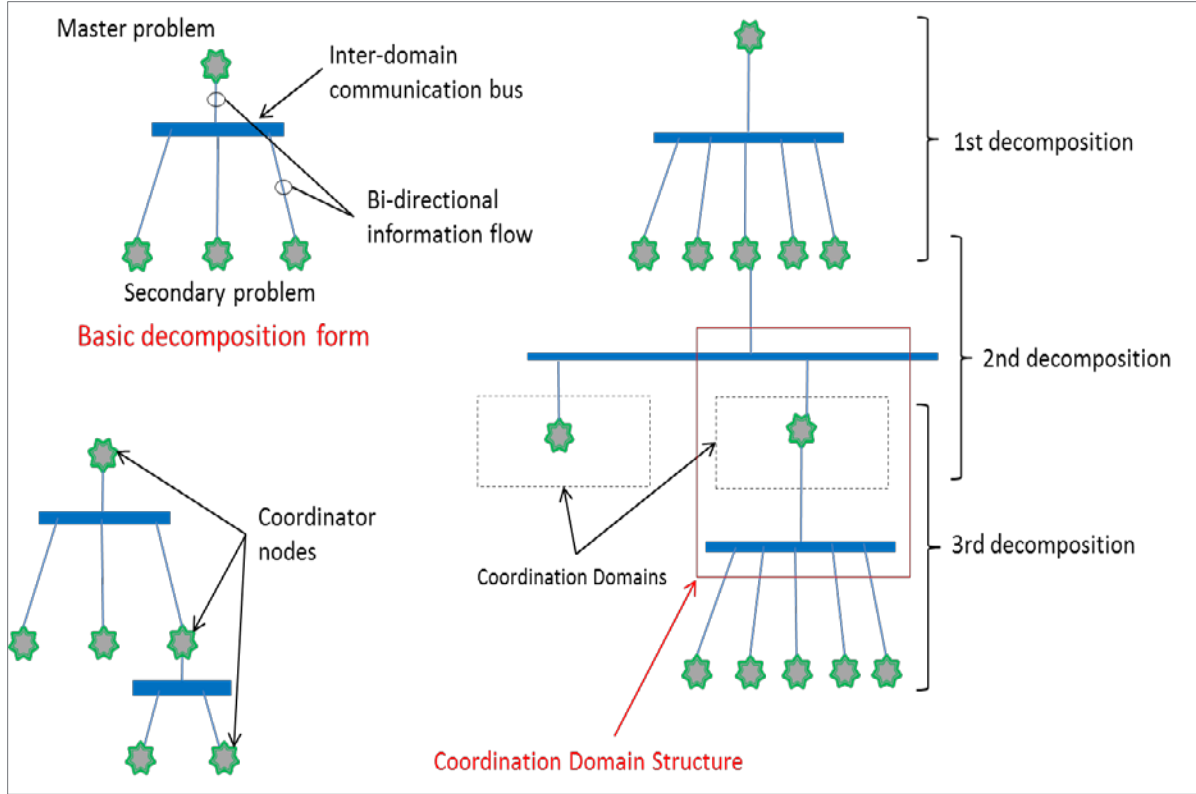


Figure 4. Underlying Layered Decomposition Structures

In the upper left of Figure 4, a single decomposition structure is shown, containing a computational node for the master problem, computational nodes for each sub-problem, and a communication bus for exchange of coordination signals. Note that *all coordination signal paths are bi-directional*. In the lower left, a two-stage decomposition is shown. One sub-problem has been further decomposed, so that there are now two communication buses for two levels of coordination signals. Finally, on the right hand side, a three-stage decomposition is shown. From this we can now identify a basic element which we designate the *coordination domain*, and a structure associated with it. This can be used as a composable¹⁰ building block to assemble complete coordination structures, which we designate *Laminar Coordination Frameworks*. . A coordination domain can be scaled as needed: it may encompass an entire Distribution Operator service area, a primary distribution substation service area, a single distribution feeder, or a feeder section and the devices connected to that section. It could also extend beyond the “grid edge” to encompass a micro-grid that has a single point of interconnection with the distribution system. Coordination domains can be and generally are nested recursively as needed. The resulting networks appear to be globally sparse but have high local clustering, and pairs of nodes in the network are typically linked by paths whose lengths are orders of magnitude smaller than the network size and grow slowly with the number of nodes. These are characteristics of small world networks, which are hypothesized to have strong robustness.¹¹

¹⁰ A composable component is one that can be assembled in various combinations (possibly with other types of composable and non-composable elements) to build systems to satisfy specific user requirements. Key properties are modularity and capability for independent deployment.

¹¹ R. Cont and E. Tanimura, “Small World Graphs: Characterization and Alternative Constructions,” *Advances in Applied Probability*, Vol. 40, No. 4, December 2008.

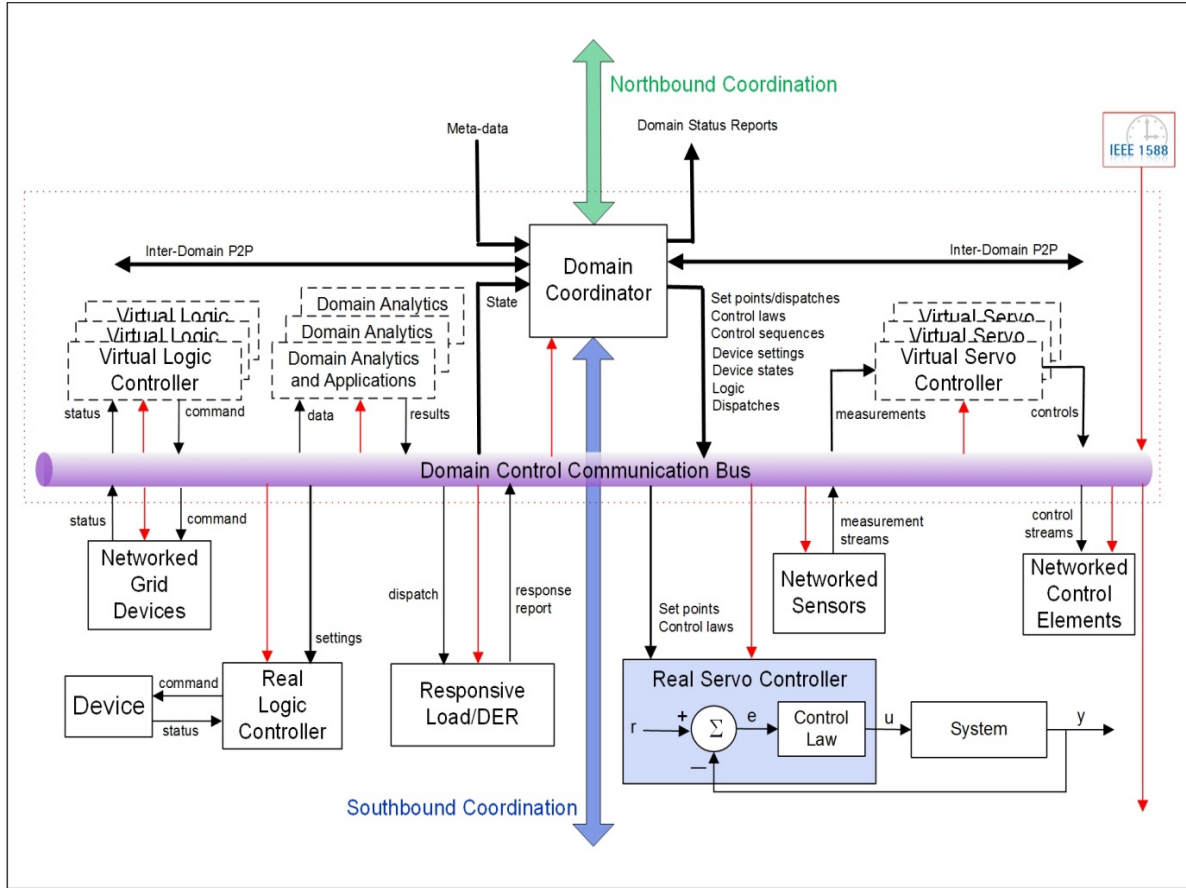


Figure 5. General Coordination Domain Internal Structure (Feeder Section Level)

Inside a coordination domain, there is a coordination node, a local communication bus and the means for northbound and southbound bi-directional coordination signal communication. The local coordination node connects to devices inside the coordination domain. Figure 5 illustrates a general coordination domain.

Coordination domains are assembled (“composed”) into larger structures that fit the decomposition model from Figure 4. The coordination node is responsible for solving its local portion of the overall coordination problem. It takes on a form that combines layered hub-and-spoke data flow with local intra-layer peer-to-peer data flow and low bandwidth inter-layer data flow. These blocks can be composed both hierarchically and recursively as needed to build up full coordination frameworks that follow the layered decomposition being employed. The Domain Coordinator Node is the computing element that can provide local services and functions within a single instance of the coordination domain. Figure 6 shows a more detailed version of the coordinator node.

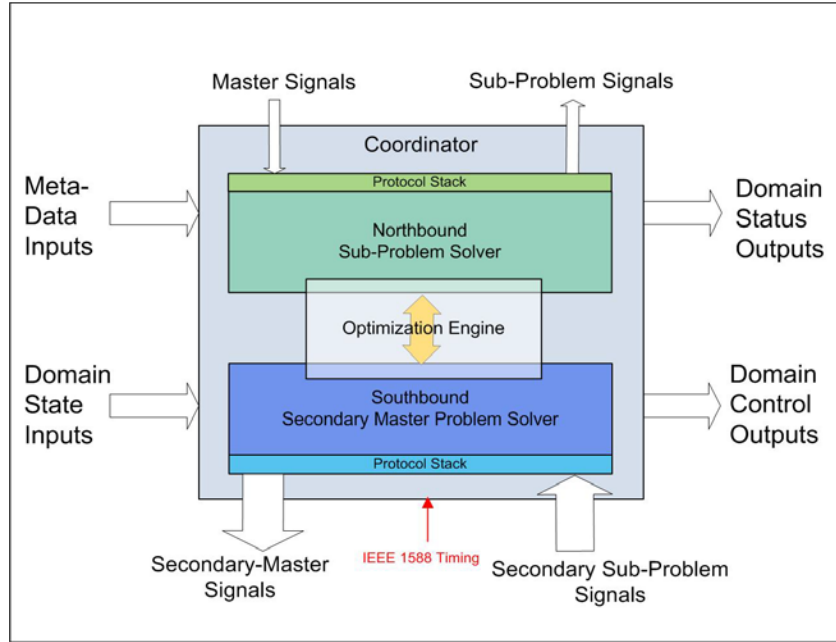


Figure 6. Coordinator Node Detail

The coordinator node may execute a traditional optimization process, or may compute a simple equation, but can also provide other computational services. *In a Transactive Energy System, it may be a Transactive Energy node.*

Figure 7 shows how a collection of such coordination domains can be composed to construct a *multi-scale coordination framework*.

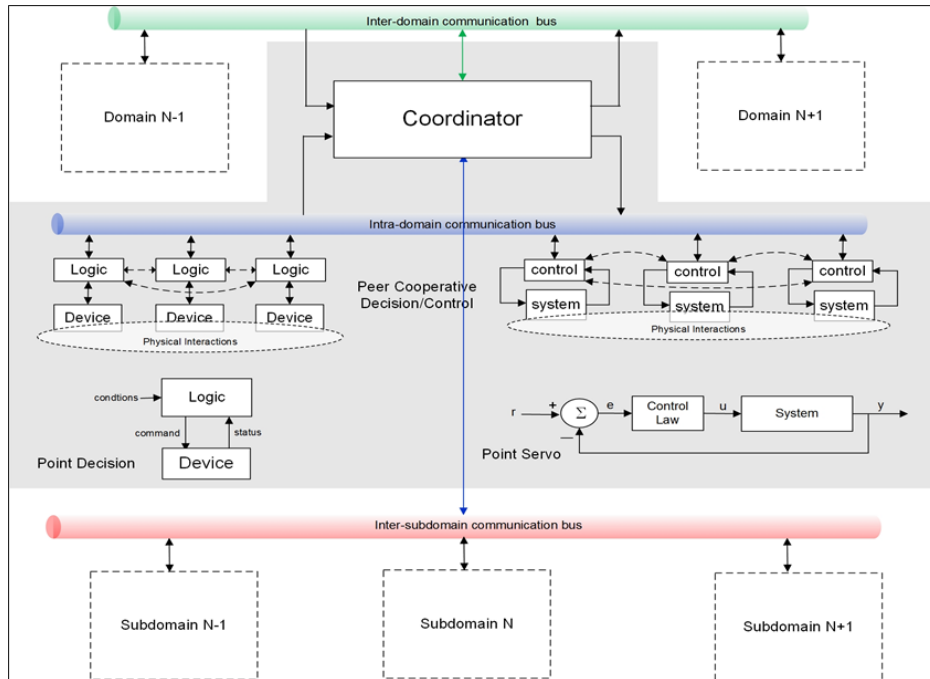


Figure 7. Partial Coordination Framework

A complete coordination framework will have a top-level or apex coordination domain and node, which will have southbound coordination communication only. Most of the coordination domains will have both northbound and southbound coordination communications, but at the edge devices, terminal coordination nodes will have northbound communication only. We can follow a path through the coordination framework from apex node to terminal node to identify a *laminar coordination chain* (the set of laminar coordination nodes in the shortest connected path from apex to terminal).

Laminar coordination networks can easily be mapped to grid structure, as illustrated in Figure 8. In practice we do not need to extend the Laminar Coordination framework all the way to the ISO or RTO. As the figure shows, decomposition structure can be specified to match the devices, subsystems, and boundaries of the grid as needed.

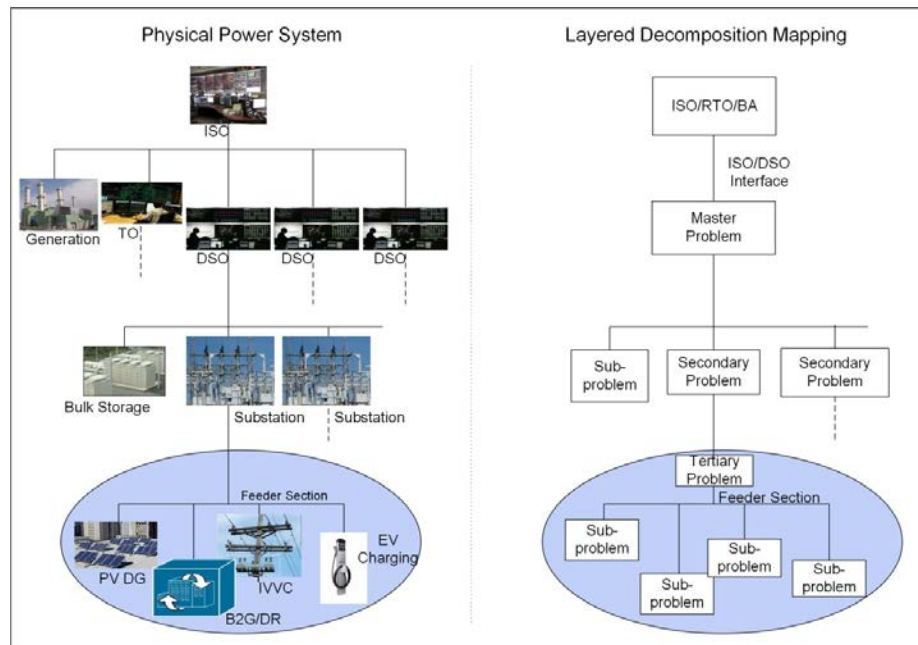


Figure 8. Mapping of Laminar Framework to Grid Structure

3.1 Key Properties of Laminar Coordination Frameworks

Laminar Coordination Frameworks have structural properties of value in highly distributed Transactive Grids. These include:

- **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.¹²

4.0 Laminar Networks

The use of layered decomposition to derive a coordination framework leads to a communication structure that can be viewed as a combination of multi-layer hub-and-spoke and peer-to-peer forms arranged in a hierarchical self-similar structure. We designate such networks *Laminar Networks* since they are the underlying logical communication structures for Laminar Coordination Frameworks.¹³ In order to study such networks, it is convenient to introduce a notational abstraction called Graphical String Notation (GSN). GSN is explained in Appendix A and are used in what follows here.

As mentioned earlier, the data flow models for coordination signals follow a layered hub-and-spoke pattern, combined with peer to peer data flows within a layer, and more general data flows inside a coordination domain among domain devices and the coordination node. Intra-domain communication will not be addressed here since it has been and continues to be the subject of much development.¹⁴ Instead we shall consider the flow of coordination signals, since this poses the more difficult and pressing problem.

The simplest approach to building a complete coordination chain would be to use a utility communication network that can reach all of the involved devices. Figure 9 illustrates this arrangement. This structure is simple, clean, and elegant. It is not however, very realistic. This is because many DERs belong to prosumers, consumers, and other third parties and are not connected to the utility internal operational communication network even though they are electrically connected to the grid.

In the case where the DERs are being aggregated or otherwise bid into central ISO markets, the communication path looks as is depicted in Figure 10. For some models under discussion in the industry, prosumer and third party DERs may possibly be bid into both ISO level and DSO level markets, leading to the arrangement of Figure 11.

¹² Jeffrey Taft and Paul De Martini, “Scalability, Resilience and Complexity Management in Laminar Control of Ultra-Large Scale Systems,” <http://gridarchitecture.pnnl.gov/media/advanced/Scalability%20and%20Resilience%20in%20Laminar%20Control%20Networks.pdf>

¹³ JD Taft, “Grid Architecture 2”, pp. 3.11-3.19, <http://gridarchitecture.pnnl.gov/media/white-papers/GridArchitecture2final.pdf>

¹⁴ S. Laval and B. Godwin, “Distributed Intelligence Platform (DIP) Reference Architecture Volume 1: Vision Overview”, <http://www.duke-energy.com/pdfs/dedistributedintelligenceplatformvol01.pdf>

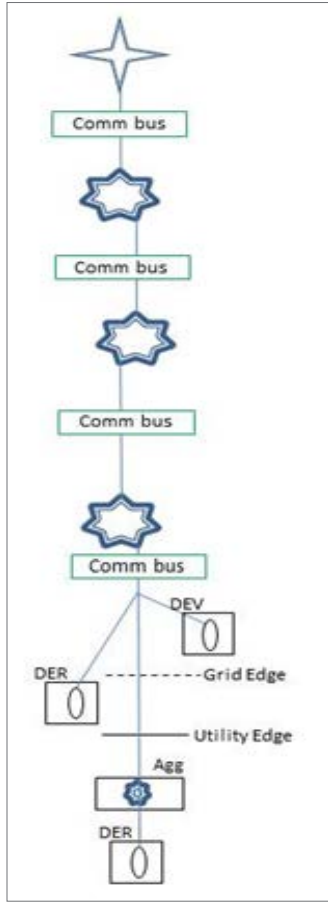


Figure 9. Basic Network

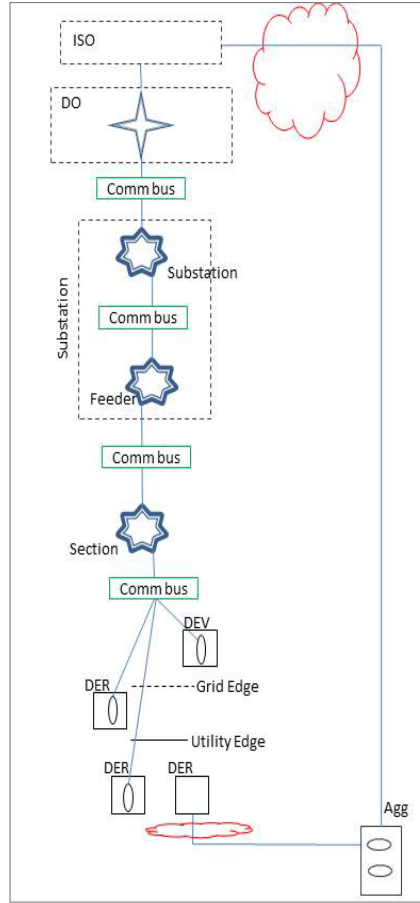


Figure 10. ISO Market Network Model

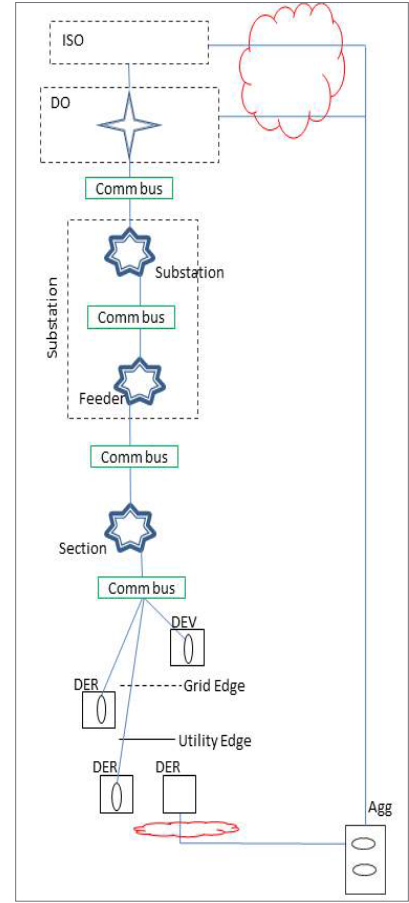


Figure 11. Two Market Network Model

The models of Figure 10 and Figure 11 do not provide the fine granularity for prosumer and third party DERs that a highly distributed Transactive Grid requires, and Figure 9 is often not a realistic option. To achieve this granularity, DERs must connect to coordination nodes associated with specific locations in the grid. Figure 12 shows two approaches to accomplishing this. The left diagram in Figure 12 shows how to complete the coordination chain by having the aggregator (or remote building energy manager or merchant DER provider) host coordination nodes for the DER assets it manages. The aggregator must have one node for each coordination domain in which it has assets and the corresponding coordination domain nodes on the grid must have a means to connect to the external network (internet) in addition to connecting to the internal utility network. This approach requires the aggregator and the DER asset to have interfaces and coordination nodes consistent with the utility's coordination framework.

Another option, shown on the right side of Figure 12, is for the aggregator to *host terminal coordination nodes on behalf of the DER assets*. In this model, the interface between the aggregator and the DER assets (which already exists in many cases) does not have to change, and the terminal nodes are very lightweight computational processes that do not pose a significant burden for the aggregator.

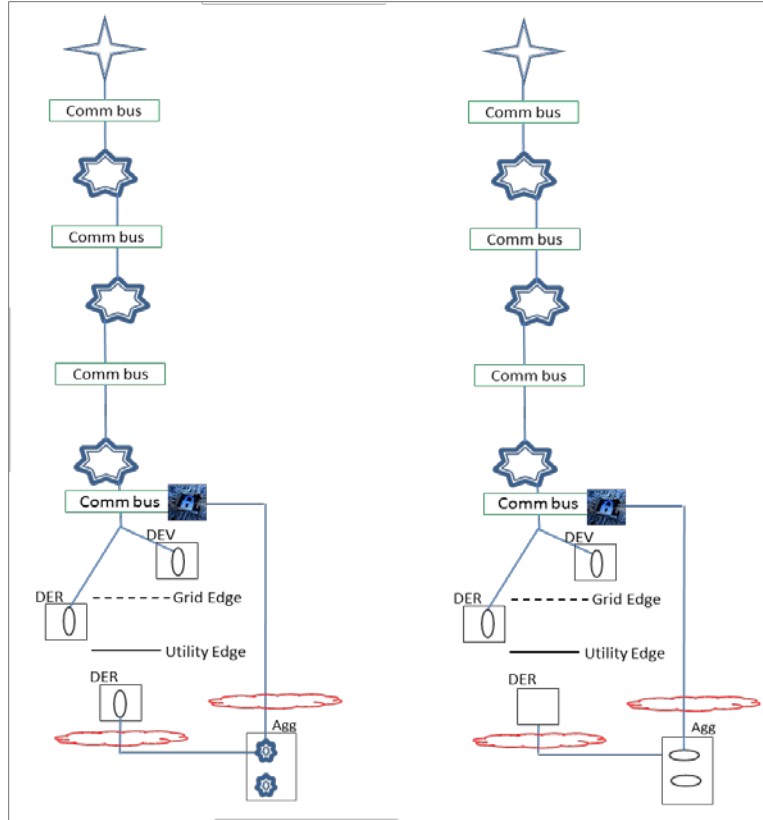


Figure 12. Laminar Networks with Granular Grid Penetration

In either coordination node-hosting scenario, the aggregator can provide a useful service to the utility by completing the coordination chains without the utility having to interface directly to the DERs.

While the laminar network models of Figure 12 satisfy the need for highly granular transactive grid, there are still two problems. First, coordination nodes throughout the distribution grid must have extra communication interfaces, and second, the high degree of external network penetration into the distribution grid implied by this approach greatly expands the grid's cyber-security threat surface. Both of these issues increase the cost of the communication networks, as well as the consequent complexity of network management.

These issues can be addressed as shown in Figure 13. On the left side of the diagram, the aggregator connects to the Distribution Operator at the distribution control center rather than at each coordination domain. A single interface to the internet (or other external network) connects the aggregator to the utility; a bridge router then provides the internal (to the utility) connectivity to connect aggregator nodes to the appropriate grid coordinator domains. This arrangement is much more easily managed by the utility in terms of security measures and cost than the arrangements of Figure 12. Some coordination signals must travel "further" to get to the control center (by moving up and down the coordination chain) than in the simple model, but these signals are lightweight and not problematic for most real networks, especially if the system control network (between substations and control center) is fiber-based. If the utility has a wireless cloud type field area network, then the coordination signals can travel to the feeder section coordination domains directly from the control center bridge router and do not have to burden the full coordination chain.

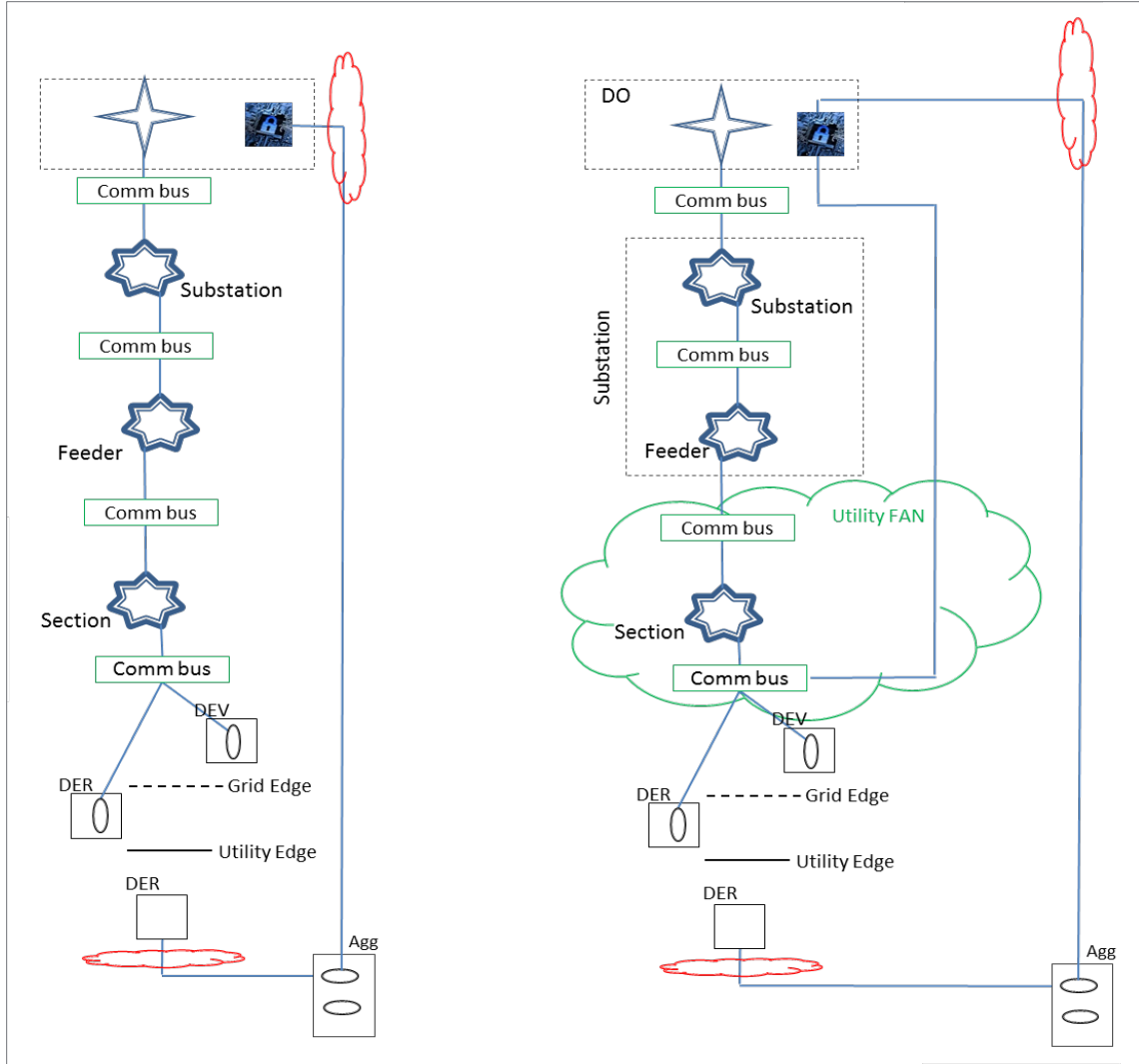


Figure 13. Improved Granular Laminar Networks

The laminar network models of Figure 13, while not as elegant as the original model of Figure 9, do provide practical approaches to completing the coordination chain while providing highly granular penetration of the distribution grid. Depending on the types of communication networks the distribution utility has, any of the models of Figure 9–Figure 13 may be used, so considerable design flexibility is available to the utility network engineer.

While Laminar Networks pose a new class of data flows for electric distribution utility communication systems, existing IP-based networking technology can easily handle the additional requirements. Most of the coordination domain data flows are contemplated by other advanced distribution automation schemes already and so the incremental impact is minimal for utilities engaged in distribution-level grid modernization.

5.0 Implications of This Approach

With establishment of an architectural framework for Transactive Distribution Grids, engineering standards for the following are easily determined:

- How many transactive nodes are needed on a grid
- Where to place the nodes
- How to interconnect the nodes

The architecture defines the data flow patterns for coordination signals, and thus informs communication network operational requirements. Standard security measures can be augmented with specific measures derived from the underlying structure of Laminar Coordination Frameworks and Laminar Networks. Finally, this architecture clarifies both interoperability standards and prosumer/third party interconnection processes.

Laminar Frameworks and Laminar Networks enable Transactive Energy Systems for electric distribution to transition from research and demonstration to practical engineering.

6.0 Transactive Distribution Grids and Transactive Grid Codes

In the US, Transmission Operators and System Operators require those who would connect to a transmission system to sign interconnection agreements. Such agreements specify a variety of business and technical terms that apply to the interconnection. In Europe, these are known as Grid Codes or Network Codes. In this document we shall use the term *Grid Code* to refer to a similar agreement for interconnection at the *distribution level*. For Transactive distribution grids, such agreements will be called *Transactive Grid Codes*.

The Transactive Grid Code is a key mechanism for a distribution utility to tell prosumers, Energy Services Organizations, integrators, building energy managers, and device/system vendors what requirements they must meet to connect to a distribution grid in a transactive manner. The Grid Code is far more than just an information interoperability standard specification. It contains physical and electrical requirements; control, communication, and integration terms; and business rules. For a Transactive Grid, the integration portions must address the combined market-control transactive mechanism in a way that ensures that externally connected devices and systems will fully and correctly participate in laminar coordination chains.

Distribution utilities are well positioned to be able to write many parts of a Grid Code, but the Transactive part, which involves a set of functionalities and interactions not previously used in distribution grids, has been problematic until now. Figure 14 shows a stack framework for Transactive Grid Code elements, with five categories of terms.

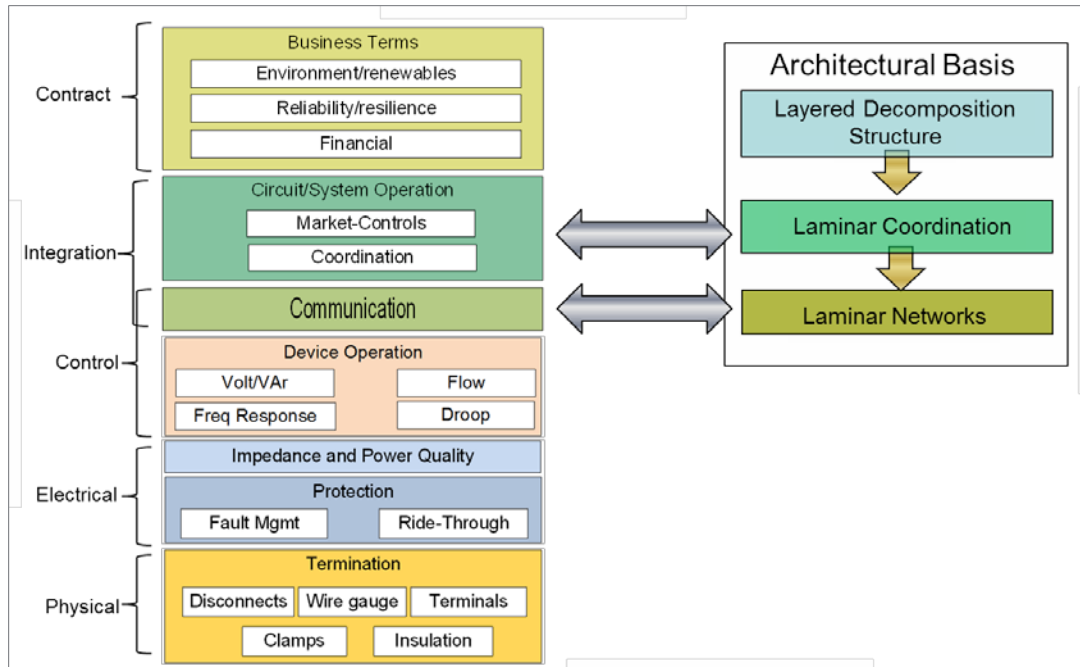


Figure 14. Transactive Grid Code Stack and Relation to Laminar Architecture

It is in the area of integration that the bottleneck has existed in terms of being able to complete a Transactive Grid Code and it is exactly this section that is addressed by architectural views provided earlier in this paper.

As utilities develop the ability to completely construct Transactive Grid Codes, the most serious impediments to the adoption of Transactive Energy Systems for electric distribution will be alleviated. This ability may be viewed as a key metric for transactive grid deployment readiness.

7.0 The Path Forward

Some states have adopted the DER interconnection agreement approach used in the Federal Energy Regulatory Commission's Small Generation Interconnection Agreement.^{15,16} These agreements do a solid job of including many business and financial terms and key electrical connection and electrical behavior issues, but do not provide any insight into how coordination between the grid and the DERs should be accomplished, either at the logical level or in terms of communications and networking. This leaves a gap that the laminar coordination framework can address.

In California, the Rule 21 Smart Inverter Working Group has done valuable work in defining functionality for DERs in general and for solar PV with smart inverters in particular. It has also had much to say about communications, but almost entirely on the level of application information exchange protocols such as SEP 2.0/IEEE2030.5, Modbus, BACnet, IEC 61850 GOOSE messages, etc. for

¹⁵ See, for example, <https://www.sdge.com/sites/default/files/documents/1653459485/WDAT%20SGIA%20-%20Attachment%20E.pdf?nid=11261> which is SDG&E's

¹⁶ See <https://www.caiso.com/Documents/AppendixS-FifthReplacementCAISOTariff.pdf> for the CA ISO approach.

communication with inverters.¹⁷ It has very little to say about network level protocols (other than mentioning TCP/IP) and does not address coordination structure and the implications for utility communication networks. Utility networks and aggregator/3rd party communications are out of scope, but this is precisely where complexity arises for the utility. This leaves a considerable gap in terms of logical functionality that must be available *on the utility side* so that the grid is able and ready to accept plug-and-play connections from DERs, especially 3rd party-owned DERs in a distributed environment and the network structure needed to support it, and leads to difficulty in specifying a complete grid code or interconnection agreement.

The laminar coordination framework and laminar network concepts can significantly augment the present work on Rule 21 in California, as well as be of value for the utilities working on architectures for distributed control and DER integration. The laminar approach can clarify interoperability standards issues; can inform how to coordinate large numbers of distribution connected resources; can show how to integrate the coordination with grid control in a distributed manner, and indicate how to structure the distribution communication networks to support DER integration, including how to manage aggregator and merchant 3rd party integration.

In light of the above, it is clear how the advance of Transactive Energy Systems for distribution grids may be driven forward. Figure 15 illustrates the flow of influence and impact, starting from architecture, and then progressing to the utilities and the interoperability standards development processes. Interoperability standards and architecture jointly inform the utilities on how to build transactive grids and write Transactive Grid Codes. Finally all three inform the transactive energy ecosystem, whose members are enabled to develop the products and services needed to implement both the transactive grid designs and the devices, systems, and services to be connected to transactive grids.

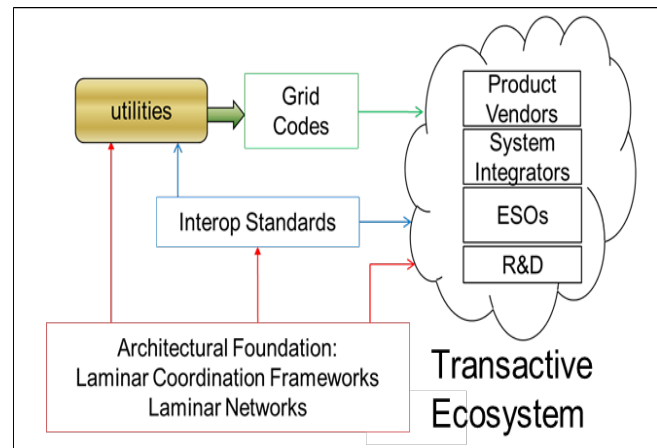


Figure 15. **Laminar Architecture Impact Flow**

Given the lead times for update of regulations, for development or completion of standards, and for approval and implementation of new utility systems and infrastructure, the following are some no-regrets first steps that various organizations can take:

Utilities:

- apply a systematic approach to determining modernization strategy with respect to DER, starting with development of well-formed goals and metrics,¹⁸ and following with grid architecture that satisfies those goals

¹⁷ http://www.energy.ca.gov/electricity_analysis/rule21/documents/SIWG_Phase_2_Communications_Recommendations_for_CPUC.pdf

¹⁸ P De Martin and L Kristov, Distribution Systems in a High Distributed Energy Resources Future, available online at http://gridarchitecture.pnnl.gov/media/advanced/FEUR_2%20distribution%20systems%2020151022.pdf

- modernize distribution level communication networks in line with the foregoing to be ready for DER integration

Standards development organizations:

- complete changes to standards such as IEEE 1547 to accommodate DER in terms of voltage and frequency ride-through, etc.,
- consider interoperability standards in light of not just information exchange, but also in the context of improved structures for data acquisition and distributed coordination and control

State Regulators:

- adopt a coordination view of DER integration to help distribution utilities in their DER-driven modernization efforts and apply the grid code approach to defining distribution level DER interconnection agreements outlined in this paper
- recognize the impact of communication networks on DER integration and encourage utilities to view communications as core infrastructure independent of siloed application systems

8.0 Summary and Conclusions

This document provides an architectural basis for developing and deploying highly distributed Transactive Distribution Grids, which are electric distribution grids in which the market-control mechanisms are distributed throughout the grid instead of being solely centralized. The mathematics of the layered decomposition approaches to solving optimization problems yields structure for the coordination of grid elements; this structure is designated the Laminar Coordination Framework. The essential building blocks of Laminar Frameworks are the laminar coordination domains, which simplify the engineering of coordination frameworks and provide the core mechanism for distributing transactive nodes throughout a distribution grid. Communication of coordination signals and other data can be structured using Laminar Networks, whose structure underlies the Laminar Coordination Frameworks.

Given this architectural basis, electric distribution utilities can not only engineer their transactive grids, they can also write the Transactive Grid Codes that define for the entire transactive ecosystem how devices, systems, and buildings can be integrated to transactive grids in a plug-and-play manner. These grid codes tie together several levels of technical specifications with the communication and cooperative mechanisms as part of a transactive (market-control) energy system and with the business rules and processes that, in total, define the transactive interface.

In terms of Grid Architecture methodology, this paper illustrates a new paradigm: select a foundational basis; extract underlying structure; determine the essential properties of the underlying structure; then use the structure and its properties to specify an architectural view set. This paradigm compares to the more common approach of either selecting from a set of design patterns that have evolved over time and practice or specifying an ad hoc structure of unknown properties.

Finally, this document also demonstrates the use of Grid Architecture methods not only to structure significant aspects of the grid, but also to organize the downstream development processes by specifying the minimum number of constraints that clarify all the other decisions to be made in the design of complex systems.

Appendix A

Graphical String Notation

Appendix A

Graphical String Notation

In order to represent a variety of coordination communication structures it is helpful to abstract the essential structure from the larger view of a grid. Figure A.1 below is a simple illustration of a utility structure with a Laminar Coordination Framework. Framework elements are represented in one of three forms: top level coordination node (four point star), general coordination node (seven point star), or terminal node (oval). Terminal nodes are coordination nodes at grid edge endpoint devices.

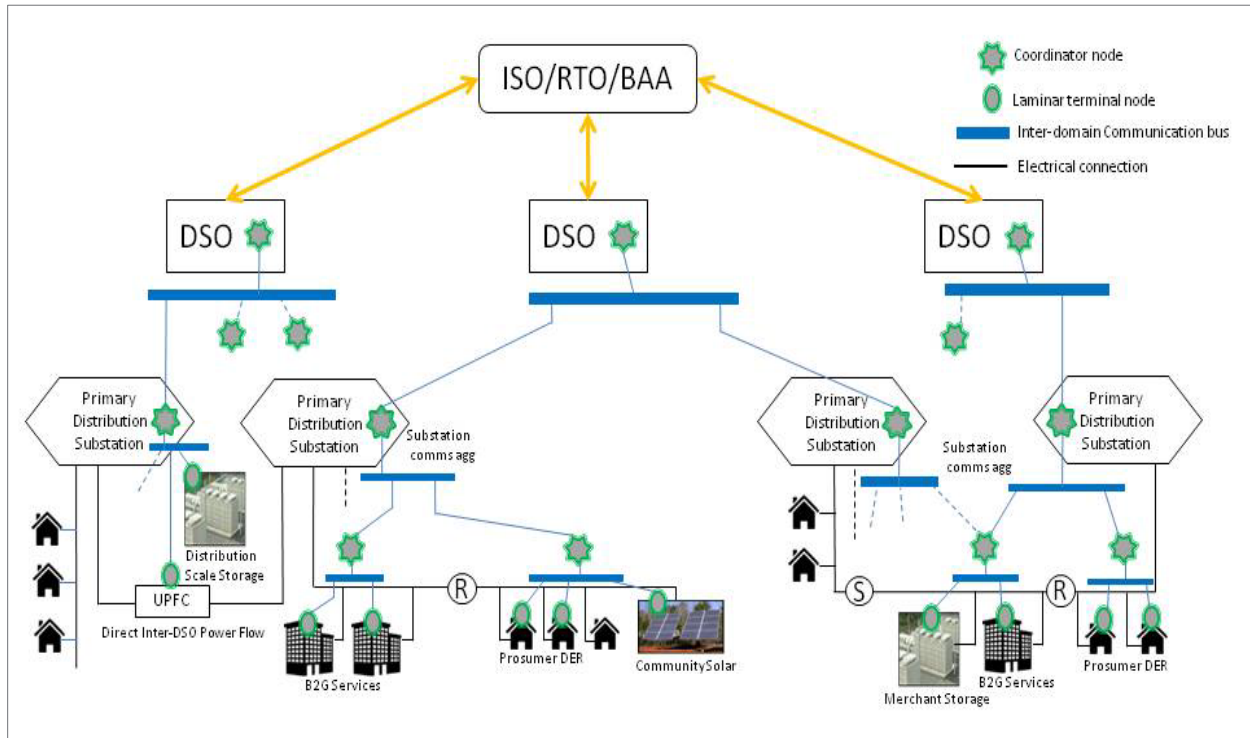


Figure A.1. Utility Diagram with Laminar Coordination

In Figure A.2, the essential coordination framework is depicted in tree structure form. The tree structure diagram is then converted to the graphical string diagram on the right of Figure A.2 by extracting the central core outlined in red. Laminar Coordination Framework elements are represented in one of three forms: top level coordination node (four point star), general coordination node (seven point star), or terminal node (oval). Connecting lines are lines of coordination and therefore communication. The boxes labeled “Comm Bus” indicate communication buses for inter-tier and intra-tier peer-to-peer communication. The grid edge and utility boundary are represented by a dashed line and a solid line respectively. Edge devices that are inside the solid line but outside the dashed line are utility-owned distribution-connected DER. Distributed-connected grid components (capacitors, switches, reclosers, grid sensors, etc.) are not considered edge devices, but as grid devices and so are inside the grid edge line.

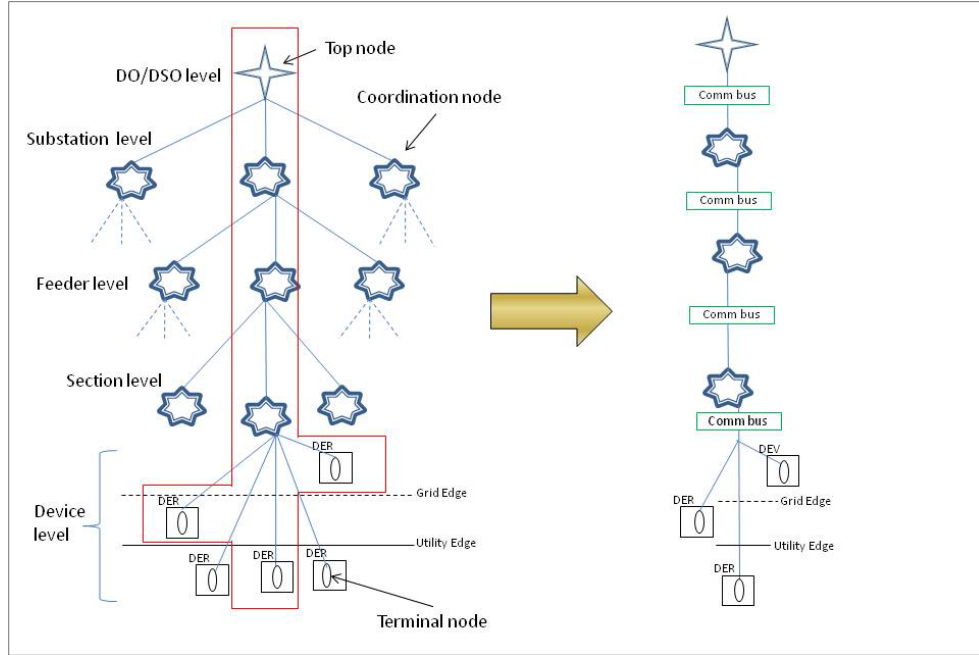


Figure A.2. Extraction of a Graphic String Model

This particular diagram pair in Figure A.2 spans the grid from DO/DSO to endpoint devices and includes devices outside the utility. In general, graphical string diagrams can reach from the TO/BAA level or even the regional reliability coordinator level through to prosumer endpoints and may also include non-utility organizations such as DR aggregators, ESOs, and merchant DER operators. In practice, most GSN diagrams will use a DO or DSO as the top level (apex) of the coordination chain. Internet communications may be represented as red clouds, and utility wireless networks may be represented as green clouds. Figure A.3 shows an example with both internet and a utility wireless field area network.

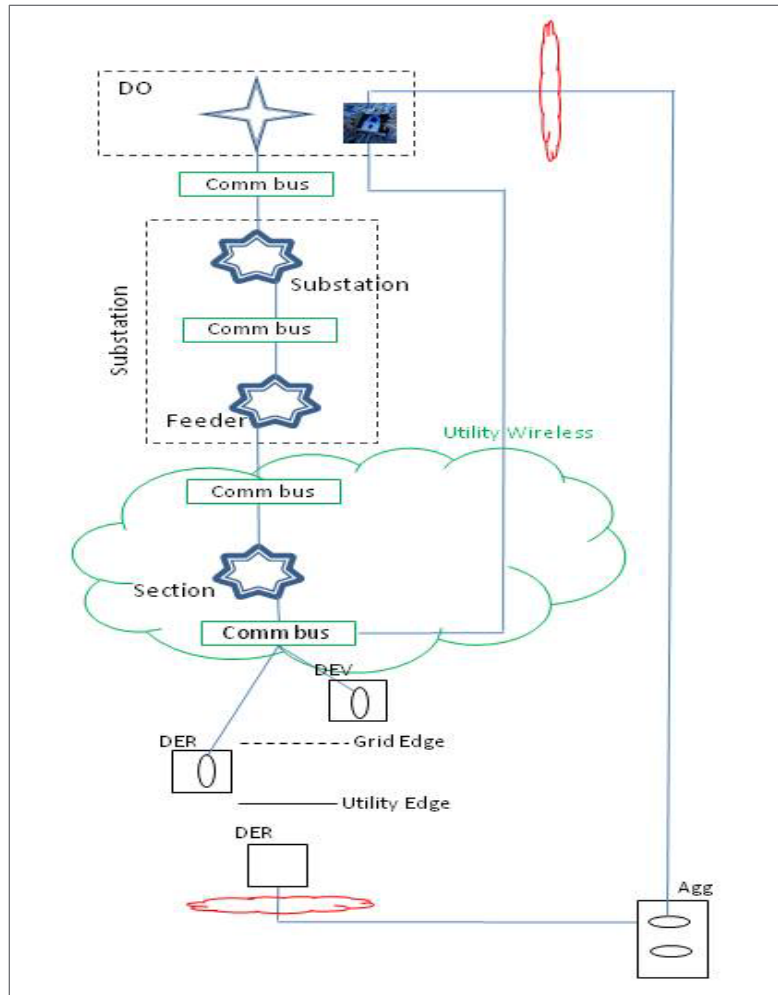


Figure A.3. Example with Internet and Utility Wireless Network



Pacific Northwest
NATIONAL LABORATORY

*Proudly Operated by **Battelle** Since 1965*

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

U.S. DEPARTMENT OF
ENERGY

www.pnnl.gov