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Architectural Framework for Variable Structure Grids

December 2021

Jeffrey D Taft

U.S. DEPARTMENT OF ENERGY

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Pacific Northwest National Laboratory
Richland, Washington 99354

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1.0 Introduction and Background

Changes in consumer expectations and emerging trends in technology are placing new demands for operational flexibility on electric power systems. These are manifest in a number of ways but one in particular has emerged in various forms (not all of which are recognized as being related): variable structure grids. Variable structure has actually existed in various forms in power grids for quite some time but recently has become popular due to the intense focus on grid resilience. Other driving forces include penetration of distribution edge connected resources and responsive loads, as well as electrification of transportation. Here we are concerned with *intra-layer structure*, which may be thought of as "horizontal" structure because it is concerned with the manner in which elements of a grid layer, such as transmission or distribution, may be electrically reconfigured.

The purpose of this document is to provide an architectural framework that can unify various approaches to variable grid structure and can aid in understanding how to plan and operate grids that can accommodate present or future structural variability.

2.0 Preliminaries

We need some basic concepts and notation from set theory and graph theory in order to proceed.

2.1 Sets

A set is a group of objects or elements related to each other by membership in a group (the set). A set is described by listing elements separated by commas, or by a characterizing property of its elements, within braces { }. For example, a set S of objects denoted by letters a, b, and c could be listed as

$$S = \{a, b, c\}$$

or by the shared characteristics, such as

$$S = \{\text{the set of lower case letters}\}$$

The elements of a set may themselves be sets. A derived binary relation between two sets is the subset relation, also called set inclusion. If all the members of set A are also members of set B, then A is a subset of B, denoted $A \subseteq B$.

If two sets have no members in common, they are said to be disjoint.

2.2 Graphs

A graph G = (V, E) is a structure which consists of a set of vertices V = {v1, v2, …} and a set of edges E = {e1, e2, …}. Each edge is incident to (connects to) an unordered pair of (not necessarily distinct) vertices. Vertices are sometimes referred to as nodes and edges are sometimes referred to as links.

Graphs are often depicted diagrammatically, such as in the example of Figure 1, with vertices shown as circles or dots, and edges as straight or curved lines. Vertices and edges may be labeled and edges may have values and/or directionality associated with them. If two vertices share an edge, they are said to be adjacent. A graph for which the edges have directionality (indicated by an arrowhead) is referred to as a directed graph or digraph. A graph with some directed and some undirected edges is known as a mixed graph.

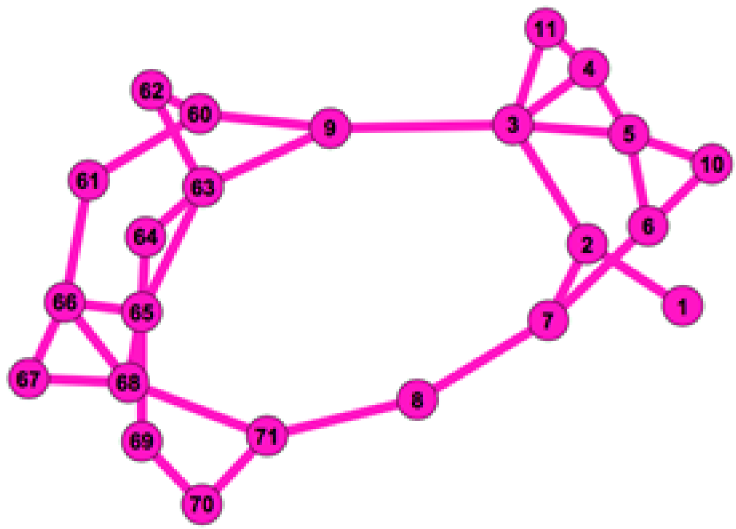

Figure 1. Example Graph Diagram

2.3 Walks and Paths

A walk is a sequence of vertices, each adjacent to the next. If all vertices in a walk are distinct, the walk is also called a path.

2.4 Subgraph

A subgraph S of a graph G is formed by a subset of vertices and edges of G. Every graph G may be partitioned into (one or more) subgraphs whose vertex sets are disjoint and whose edge sets constitute the edge set of G. These subgraphs are called the connected components of the graph. A graph may be partitioned into subgraphs. When there is no path from one subgraph of a graph to another, they are said to be disconnected.

2.5 Connectivity

A graph is said to be connected if it has at least one vertex and there is a path between every pair of vertices.

Electrical structure is defined by electrical connectivity. Electric connectivity does not exist between two vertices if the electrical admittance (conductance in DC systems) between them is zero. Hence for this purpose, connectivity is a binary (switching) property. Modulating or adjusting flow does not change physical grid structure, so a power flow controller embedded in the grid does not change physical structure any more than a valve would change the structure of a piping system, except to the extent that it could completely stop flow, or allow flow in some amount. However, whether we are considering switches or power flow controllers that can completely shut off the flow of real power, we may view the underlying physical structure as having two representations:

1. As-built structure – the complete physical circuit set, without regard for the states and any switches or flow controllers

2. As-operated structure – the *effective* structure, taking into account the settings of switches and power flow controllers

This two-view approach is consistent with operating procedures at many electric distribution utilities. When we consider variable physical structure, we are primarily concerned with the as-operated structure. This is reflected below in the way we define a grid.

2.6 Electric Power Systems as Graphs

Electric hardware components are basic elements of electric power circuits: transformers, sensors, controls, switchgear, protection devices, insulators, poles and towers, etc., interconnected by wires. We also include storage devices, grid edge-connected generation, and loads. From our grid-centric point of view, loads and microgrids are bounded at a facility disconnect switch or point of common coupling, which may be at a meter in the case of a building. We do not extend this view inside a building, generation facility, or microgrid here but the definitions below are general enough to permit that if it is useful.

We can represent electric power systems as graphs where edges (links) are circuit lines (wires) and vertices are "intersection" points, such as at transformers, switchgear, taps, branches, infeeds, protection and control devices, and load connections.[1] If we allow for reversible power flow in the wires, then edges are simple links. If for some reason a particular electrical path only allows one-way flow of real power, then the edge must be directed (represented as a link with an arrow).

Graphs provide a means to represent grid physical structure and graph theory offers ways both to characterize and to transform such structures. As we shall see, representing power systems as graphs constructed of interconnected subgraphs will provide a multi-scale framework for working with variable grid structure.

[1] Note that for other purposes this may be reversed – circuit lines may be treated as the nodes (think "node voltage") and devices such as transformers and switchgear may be treated as the edges or links.

3.0 Conceptual Framework

3.1 Logical and Physical Structure

In order to provide a general unifying framework for variable structure grids, we need two kinds of views: a physical view that focuses on actual electric infrastructure hardware, and a logical or virtual view that employs some amount of abstraction for the purposes of structuring coordination and control in a manner that supports many possible implementations of variable structure grids. The logical or virtual views derive from the work on Logical Energy Networks[1] (LENs) and Laminar Coordination Frameworks.[2]

For physical structure, we introduce a modest amount of formalism for the definition of power grids in a set and graph theory context.

3.1.1 Definition 1: Grid Segment

Grid segment = {electrical hardware components that are electrically connected}

Electrically connected components may be grouped or associated with each other as a unit, which we shall refer to as a grid segment. A grid segment must be electrically connected and could itself be represented as a graph. *Segment structure* is defined by the association and interconnection of the electrical hardware components.

Note that “grid segment” is a multi-scale (and hence recursive) concept - a grid segment may be:

- a distribution circuit section
- a complete feeder circuit
- a microgrid
- a whole distribution system
- a transmission line
- a transmission system
- a whole regional interconnection

The boundaries of a grid segment are typically determined as part of system planning, with implications for engineering and operations. Grid segments are disjoint sets of electric components. Even though at one scale we may view segments as graphs for purposes of their internal structure) we may treat grid segments as vertices (nodes) in a graph at the next higher level of scale. Figure 2 illustrates a multi-scale view of grid segments. For the Bulk Power System, a connected (via substation switchgear) distribution system can be a grid element,

[1] JD Taft, Logical Energy Networks Concept of Operations, January 2019, available online: https://gridarchitecture.pnnl.gov/media/zip/High_Resilience_Ref_Arch_March_2019.zip

[2] 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

whereas at the distribution level, feeder sections separated by reclosers can constitute grid segments.

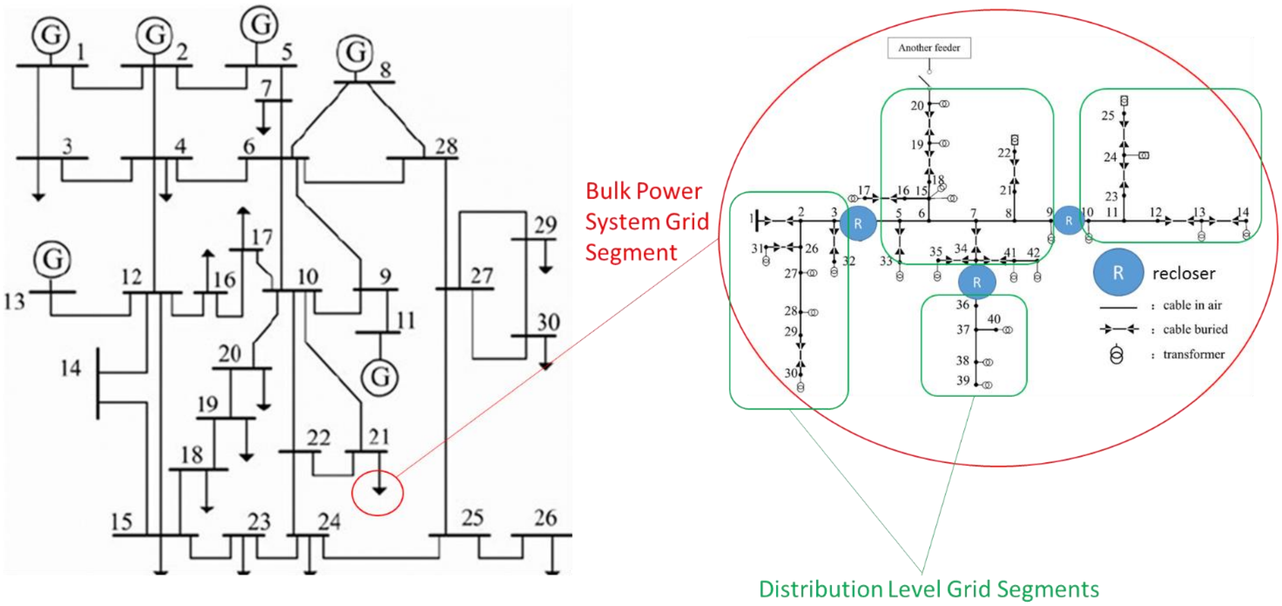

Figure 2. Multi-Scale illustration of Grid Segments

3.1.2 Definition 2: (Electric Power) Grid

Grid = {grid segments that are electrically connected}

An electric power grid is an electrically connected set of grid segments. *Grid structure* is defined by the interconnections of the segments. This is consonant with the standard operating concept of as-operated configuration, but applies more widely when considering microgrids and other forms of grid modularity. We may therefore represent a grid as a graph wherein the vertices are grid segments and the edges are the electrical interconnections among the grid segments. Such an approach allows us to operate at any scale by selecting the element type that is to be treated as a segment from the bulleted list above.

3.1.3 Definition 3: Variable Structure Grid

Variable Structure Grid = {segments, utility switches, external device switches}

A physical variable structure grid is one whose structure may be altered by changing connectivity via switching. Grid segments (represented as subgraphs) may be connected, disconnected, and/or reconnected. Utility switches are switching devices controlled directly by the electric utility. External (to the grid) device switches are switches controlled by attached devices such as loads or by third parties managing externally connected devices and systems. The as-built structure of the grid is determined by the settings of the switches and can be quite dynamic.

This definition is broad and it will immediately be clear that many common practices in grid design and operation are included this definition. That is intentional and is discussed in more detail below.

3.2 Virtual Structure

Virtual structure can exist in concept and in software representations. Just as with virtual machines in computing, we may view the grid at the virtual level as being multiple grids operating independently, each ultimately supported by the underlying physical grid. In that regard, we may then consider multiple power flows, each of which may be between any two vertices. This leads to the concept of N-way power flow, where the N ways are composed of the set of simple virtual power flows. Each virtual flow operates on a virtual grid and each virtual grid has its own graph. The elements of the set of virtual graphs are not necessarily disjoint.

For the physical system, real power flow at any point in a circuit at any specific time is one-way.[1] N-way power flow can only exist in virtual systems, and so 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. Therefore it cannot be a simple superposition of the virtual power flows. The set of virtual graphs can resolve into a union of the virtual graphs that must map onto the actual physical grid graph. Since this resolution cannot just happen automatically, a process is needed to perform the resolution and produce the resulting scheduling of flows, which may require reconfiguration of the grid.

For purposes of understanding how to operate on virtual flows, we represent individual power flows as digraphs. The digraphs are initially all generated separately. During the resolution process, these flow graphs (where the edges have values that are the magnitudes of the real power flows) must be combined into a single flow graph that maps to a grid. The grid must support the resolved power flow and so may need to be reconfigured dynamically. This leads to a need for simultaneous solution of flow and grid structure. This is a common and solved problem at the Bulk Power System level but is not solved at the distribution level.

3.3 The Five Layer Model

Combining the LEN/Laminar concepts with these definitions results in the five layer model for variable structure grids shown in Figure 3.

[1] While the term two-way flow is often used in connection with modern power grids, this is a bit of a misnomer. Communication networks that can have full duplex flow, but power circuits do not and the term two way flow really refers to *reversible* flow. At any instant, real power flow is one way.

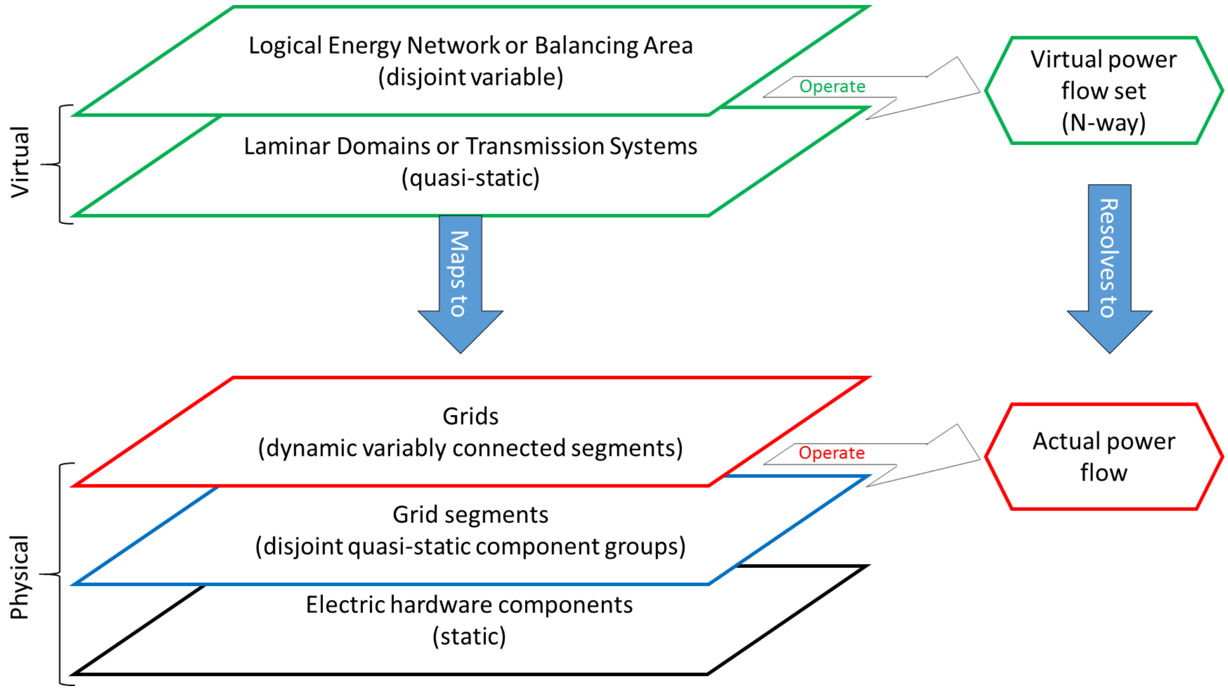

Figure 3. Five Layer Model for Variable Structure Grids

Control and coordination resides in the upper virtual level. At this level, power flow is viewed as a collections of virtual flows, each of which related to some aspect of grid operations and may include reverse flows and peer-to-peer flows in environments where the grid is treated as a network that facilitates various energy exchanges. Consequently, at this level, the grid is considered to support N-way (virtual) power flow, consisting of the set of all individual conceptual power flows. The virtual elements map onto the physical system in a flexible manner. It is this flexible mapping that is <u>the basis for variable structure at the virtual level</u>.

At the virtual level, the structure of Laminar coordination is somewhat related to underlying electrical components but is mostly a software construct and so is classified as quasi-static.[1] Logical Energy Networks and their Bulk Energy System homologs are changeable and support variable structure at the logical level. The time scales for such variability at the bulk system level are slow enough to be considered quasi-static. At the distribution level LENs certainly *could* be changed quickly but more likely would be fairly stable and so generally would be quasi-static.

3.4 Grid Structure Control and Adaptivity

Once the variability of grid structure is established, a question arises as to how the structure itself is controlled. At the physical level, we have a fairly simple paradigm for the formation of grid structure:

Associate components into segments → Connect segments → Operate grids

In a variable structure grid, association of components into grid segments is a **planning** function, whereas connecting grid segments via switching to form a grid is an **operational**

[1] Changing so slowly (with respect to a particular timeframe) as to appear fixed. Here the time frame is real time grid operations (milliseconds to hours).

function. Consequently, we view the entire set of electrical components as static on operational time scales. Grid segments can be re-associated with some effort and so are classified as quasi-static. Grid and external device switching can be done on short time scales and so are classified as dynamic. It is this switching that is the basis for variable structure at the physical level. Control of grid structure (interconnection of grid segments) is an operational issue and therefore a real time grid control issue.

Figure 4 below shows the relationships between structures and processes.

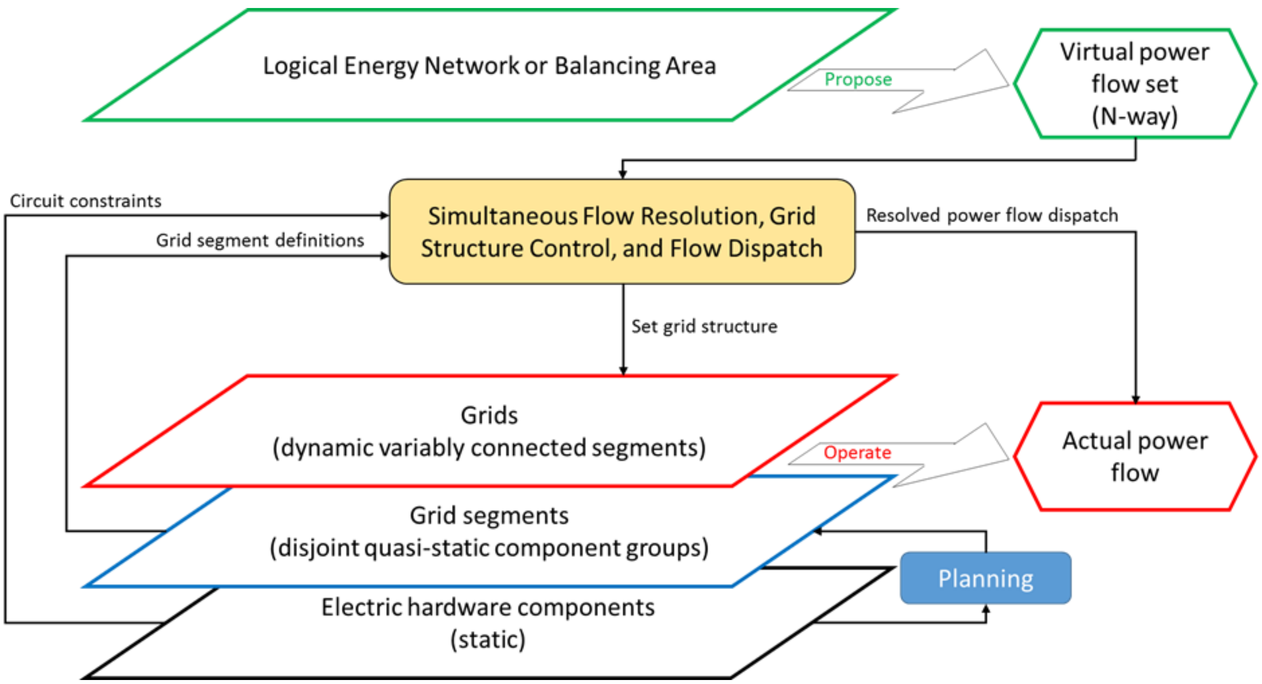

Figure 4. Grid Structures and Core Control Functions

In present practice, structure control is typically done via manual control and SCADA. In future flexible grids, this will require a new real time control functionality to automatically reconfigure grids to accommodate changing operating conditions at higher speeds than can be done with human-in-the-loop operation.

Extensive use of variable grid structure implies the need for a new distribution-level automated real time control functionality (*control of grid structure*) integrated with traditional grid control.

3.5 The Relationship of Vertical and Horizontal Structure

Previous work on Laminar Coordination has established a vertical structure for grid coordination architectures. Laminar Networks are multi-scale tree (“vertical”) structures with inherent support for distributed coordination and control. The introduction of the Logical Energy Network concept provides a basis for virtual structural modularity in power grids. The principles outlined in this paper provide a basis for physical structural variability in power grids, which addresses an aspect of “horizontal” structure. The combination of these concepts yields a model for extensive grid flexibility within a regularized[1] layered framework. The upper layers of this combined structure are virtual in nature but must map to and conform to the constraints of the underlying physical grid. The Laminar Network provides the transition to connect the virtual view of the grid at the Logical Energy Network level to the physical circuit level. The LEN may map to one or more (contiguous) grid segments. Some of the switching or power flow devices that connect grid segments may map to the boundaries defined at the LEN virtual level. In this fashion, the vertical and horizontal structures can be integrated.

[1] In the sense of introducing information to solve an ill-posed problem.

4.0 Variable Structure Grids in Practice

Many aspects of existing grid operations involve variable structure. The fact that the concept of as-built vs. as-operated grids exists is a clear indication, but other aspects exist as well. At the transmission level, switching stations, protection, and substation switchgear provide variable structure. Circuit breakers and other forms of protection fit the definition of variable structure, as does the islanding of microgrids and connection/disconnection of buildings. FLISR[1] is a form of variable structure, one that can operate autonomously. Partially meshed distribution feeders with interconnection switches are certainly variable grid structures.

Note that at the Bulk Power System level, simultaneous solutions for grid structure, power flows, and, where organized wholesale markets exit, market clearings, are standard practice. The optimization solution makes use of all of the individual proposed power flows, including baseload bilateral contract flows to develop the actual power flow solution. In that case, the power flows can be treated as a set of power injections and take-offs in a three-phase system that must balance (in the no-storage case). For distribution systems that are acting as energy transaction networks, unbalanced three phase operation and other factors would make the situation more complex.

[1] Fault Location, Isolation, and Service Restoration

5.0 Newer Concepts in Variable Grid Structure

In the last several years, new approaches to grid operation have been proposed. Several of these either use variable structure directly or imply its use.

5.1 Microgrid Networks

Thinking and practice in this area has progressed from single user microgrids, to multi-user microgrids, and to networks of microgrids. At the networking level, one may consider that the interconnection of individual microgrids into networks may be switchable, so that each microgrid fits the definition of a grid segment, and the network of microgrids fits the definition of a grid as given in this document.

5.2 Agile/Fractal Grids

This approach is in concept very similar to the idea of microgrid networks, but with the added element of cooperation and support among the individual "cells" of the agile/fractal grid[1,2] and with the idea that configuration is extremely flexible, so that unlike traditional microgrids, the associations are dynamic. In practice, this would seem to imply a large amount of switching to implement the dynamic association, which really just redefines the grid segments to be quite small.

5.3 Adaptive LENs

The LEN approach uses virtualization (and to some degree, physical accommodation) to define modular grid structure. Making the LEN definitions dynamic opens up the possibility of making LEN boundaries adaptive, meaning that a LEN may map to some variable set of contiguous grid segments. This might be done algorithmically at the LEN level via the grid structure control that was hypothesized above. Thus the adaptive LEN concept subsumes the Agile/Fractal concept (because LENs can be but do not have to be microgrids).

[1] M. Martin, Overview of the Agile, Fractal Grid, NREL, May 2017.

[2] C. Miller, The Future Grid: Engineering Dreams, March 2017.

6.0 Final Comments

Using notions from set and graph theory, we have defined the concept of variable structure grids as a multi-scale, multi-layer model, with both physical and virtual levels and have indicated conceptually how these are related. This definition allows us to unify various existing and emerging practices and concepts into a unified framework for Variable Grid Structure; this unification provides the core principles upon which to base a reference architecture specification. The framework also identifies a new class of grid control functionality for electric distribution systems that exists only in limited, mostly manual supervisory forms now: grid structure control.

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

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