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Selected Grid Architecture Principles and Consequences

September 2019

Jeffrey D Taft

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Contents

Figures

1.0 Introduction

In addition to the general principles of good system architecture, there are specific Grid Architecture principles that derive from electric power grid considerations. These principles have specific implications for both Grid Architecture methodology and specific grid architecture instances. In this document we lay out several of these principles and their implications in the practice of Grid Architecture.

2.0 Architecture Definition

An architecture is an abstract depiction of a system that we use to reason about the system's structure, behavior, and characteristics. It is the highest-level view of a complex system and is comprised of three types of elements:

- black-box components
- structure
- externally visible characteristics.

The discipline of system architecture assists stakeholders in the following ways:

- It enables reasoning about a system's structure and behavior.
- It enables prediction of system characteristics.
- It manifests the earliest design decisions/constraints; it "shapes" the system.
- It defines essential limits in the form of enforceable structural constraints.
- It helps stakeholders understand the whole system and the implications of change; it aid in removing existing structural barriers.
- It helps manage system complexity and therefore risk.
- It facilitates communication among stakeholders (internal and external).
- It helps identify gaps in theory, technology, organization, regulation, etc.
- It helps identify and define interfaces and platforms.

System architecture differs from design in that architecture is focused on large system issues rather than implementation details. An architecture sets the essential bounds on a system and as such admits more than one possible design. A design, by contrast focuses on details and admits only one implementation. Figure 1 illustrates this concept.

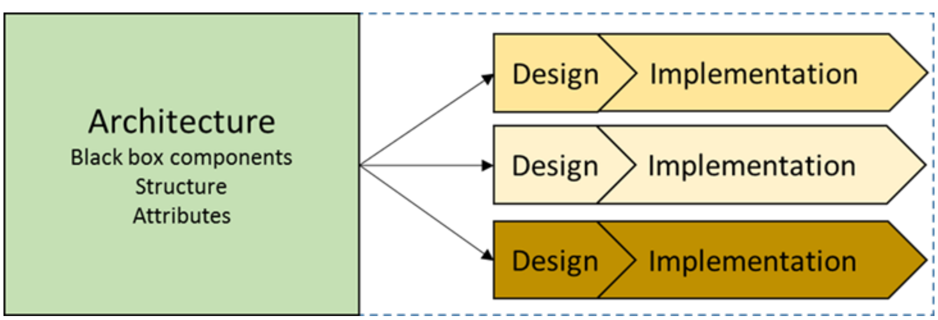

Figure 1. Relationship of Architecture, Design, and Implementation

Grid Architecture is a specialization of system architecture, based on a combination of system architecture, network theory, control engineering, and software architecture. It provides a high-level view of the electric power grid that enables reasoning about the grid's properties, behavior, and performance.

Grid Architecture is mostly focused on *structure*. This is because structure sets the essential limits on what the grid can and cannot do, leading to two important reasons for this focus early on in the grid modernization process:

- Get the grid structure right and all the pieces fit into place neatly, the downstream decisions are simplified, and investments can be future-proofed.
- Get the grid structure wrong and integration is costly and inefficient, grid investments are at high risk of being stranded, and modernization benefits realization may be extremely limited

Architecture is more akin to strategy and planning; design is more akin to engineering and operations. Architecture delimits design and implementation just as strategy delimits engineering and operations as Figure 2 illustrates.

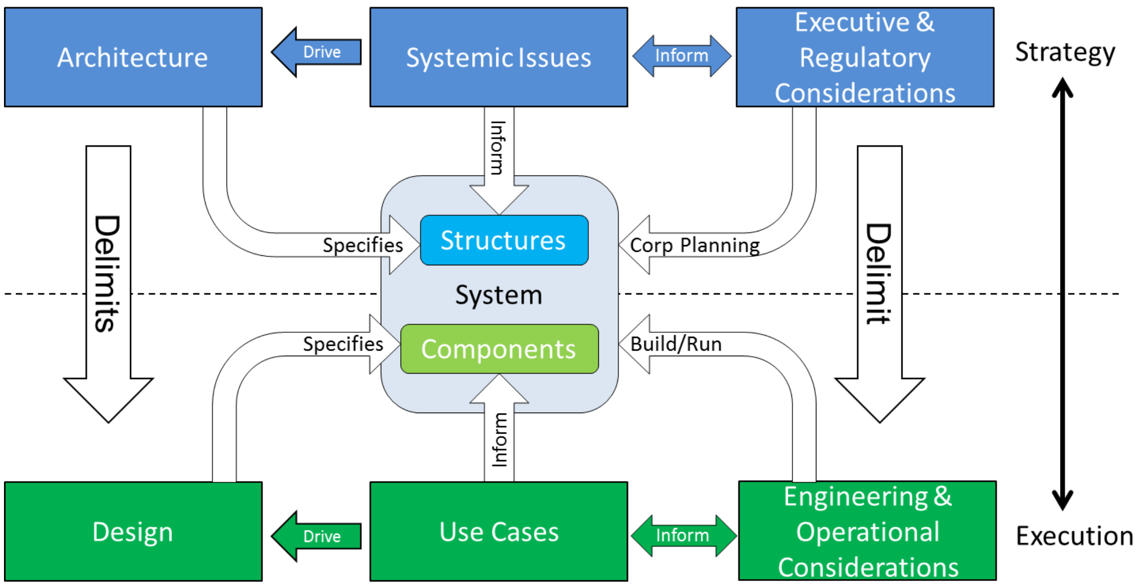

Figure 2. Relationship Architecture and Design to Planning and Execution

Grid Architecture differs from *systems engineering* in terms of both problem focus and sequence. Systems engineering is concerned with the design, creation, and operation of systems from subsystems. As such, it is component-focused rather than structure-focused and presumes the existence of a set of sub-systems (components in architecture terminology, but "box level" or higher in terms of integration and complexity, i.e. vendor products). It is concerned with the integration of those components (assembling the building blocks), and the operation and management of the resulting systems throughout their life cycles. Like enterprise IT, systems engineering is concerned with the internal structure of the systems it is assembling, <u>but not with adapting or modifying the greater structures into which they must fit</u>. Systems engineering is part of the design and operations phase, and so makes use of the outputs of the grid architectural phase. In the case of grid modernization, we must be concerned with these larger issues because we have inherited much structure from the 20th Century grid and in many case legacy structure poses constraints on new functionality. Such constraints must be relieved so that new capabilities or improved grid characteristics may be implemented and realized. Figure 3 shows the sequential relationship of architecture, design, and systems engineering.

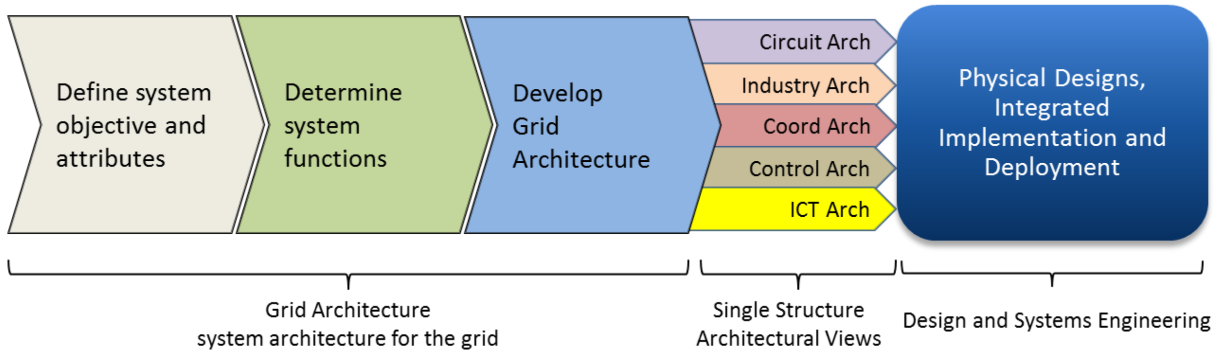

Figure 3. Sequence of Architecture, Design, and Systems Engineering

3.0 Principles

3.1 Complexity

The hidden problem in dealing with grid modernization is the sheer complexity of the grid. It goes far beyond the complexity of many other kinds of system and in fact has a special name: Ultra-Large-Scale (ULS) Complexity. The basic theory is from *Ultra-Large-Scale Systems: The Software Challenge of the Future* (Feiler et al. 2006), which is available online. The basic presumption in the book is that some classes of systems have levels of complexity that "…push far beyond the size of today's systems and *systems of systems* by every measure…." The book cites the Department of Defense and U.S. health care as examples of ULS systems. A system can be identified as ULS if it has one or more of these defining characteristics:

1. inherently conflicting diverse requirements
2. decentralized data, control, and development
3. continuous (or at least long-term) evolution and deployment
4. heterogeneous, inconsistent, and changing elements
5. wide time scales
6. wide geographic scales
7. normal failures

Power grids clearly exhibit Ultra-Large-Scale complexity on many of these dimensions. Note that the Ultra-Large-Scale complexity of the grid applies at all scales from individual distribution utility to regional interconnection. ULS complexity of electric grids does not derive from the number of components or geographic extent. It derives from the fact that electric grids are comprised of multiple complicated structures *and* these structure are interconnected in complicated ways, which results in an exponential increase in complexity over that of any individual structure.

Complexity management is a key aspect of grid architecture.

A consequence of ULS complexity is that it is <u>not feasible to drive grid architectural development from use cases</u>. Due to both the complexity and continual change, it is not possible to generate a complete library of use cases, and any attempt to do so results in such a large set that they become impossible to even navigate, let alone understand in a comprehensive way.

To resolve this issue, grid architecture development is driven by <u>systemic issues</u>. Some macro uses cases ("scenarios") are employed as sanity checks on proposed grid architectures. Figure 4 illustrates the inputs to the grid architecture development process.

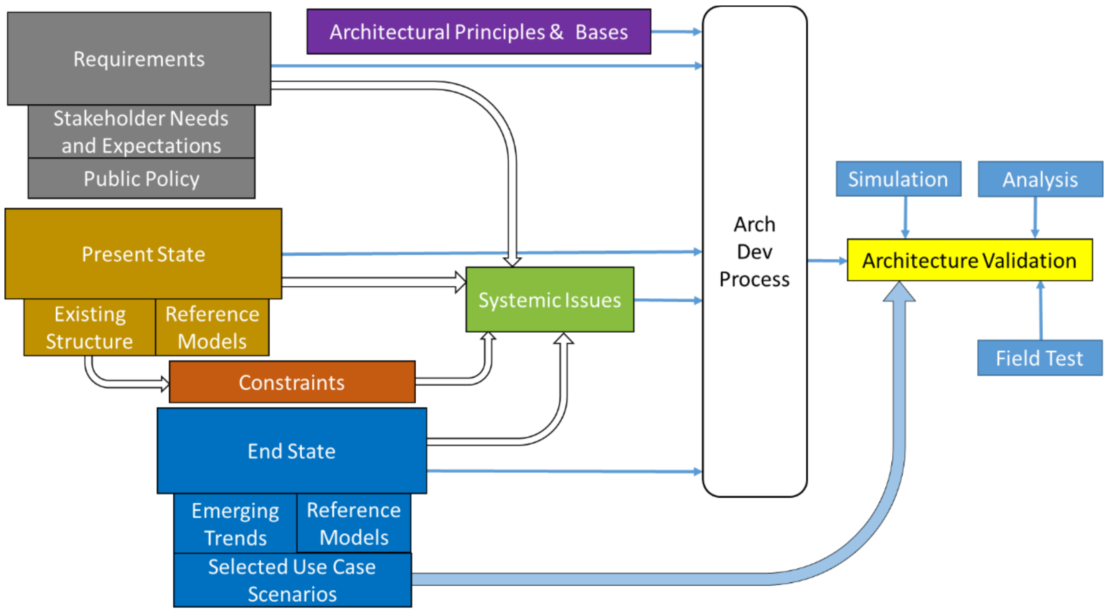

Figure 4. Driving Architecture via Systemic Issues

> The set of systemic issues for a grid modernization problem is of manageable size and is stable; the set of use cases is almost unbounded and is continually changing. Employing systemic issues instead of use cases for architecture development is a valuable complexity management technique.

Architecture and systemic issues are fundamentally strategic in nature and consequently relate well to utility business planning, regulation, and large scale modernization questions. Focus on structure is consonant with large scale, top-down system thinking and broad scope. Design and use cases are fundamentally execution-oriented in nature and so relate well to engineering and operations. The focus on components is consonant with fine detail and narrow scope.

> Systemic issues provide the wide angle lens whole system views; use cases provide the microscopic detailed system views.

3.2 Layered Decomposition and Platforms

Layered decomposition is a mathematical technique for breaking down a large scale optimization problem into a recursive set of sub problems. While it can and has been used to solve grid control problems, it has another use: the mathematics can induce a structure whose intrinsic properties (such as scalability) are known.[1] This structure then can be used as a framework for many architectures and designs. The layered decomposition method is the basis for th structural underpinnings of some of the Distribution System Operator (DSO) models being

[1] J. Taft (2016), Grid Architecture 2, Pacific Northwest National Laboratory; PNL-24044 2, January 2016, available online: https://gridmod.labworks.org/sites/default/files/resources/Grid%20Architecture%202%20final_GMLC.pdf

considered for Transmission/Distribution coordination. [1] Figure 5 shows how layered decomposition induces structure.

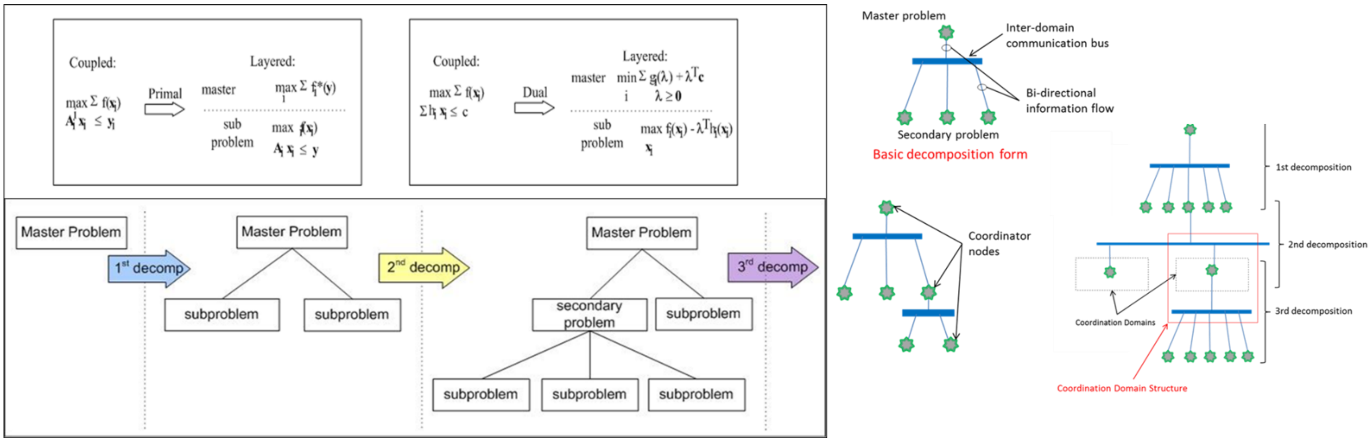

Figure 5. Layered Decomposition Induces Structure

> Layered decomposition provides a template for how to structure the grid to accomplish many functions within one framework, thus simplifying overall architecture. The structure template can be used without the need to solve mathematical equations.

Layering is itself a valuable architectural concept. In general, systems may be built in the form of layers stacked on each other. This approach is widely used in computing and communication systems, and can be applied generally to the grid. One of the advantages of layered systems is that each layer can insulate the layer above the intermediate layer from changes in the layer below and vice versa.

A platform is a stable collection of components that provide fundamental or commonly-needed capabilities and services to a variable set of uses or applications through well-defined interoperable interfaces. Key properties of a platform include:

- It separates foundation functions from end uses (“applications”) via layering
- It provides a set of services and capabilities that are useful to many applications
- The platform is stable over time, while the applications may change frequently
- It provides decoupling of changes between applications and underlying infrastructure
- It may scale (adjust resources) to support variable demands from applications
- It is open: third parties can freely create applications that use the platform (needs open standard interfaces to do this)

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[1] De Martini P and L Kristov. 2015. *Distribution Systems in a High Distributed Energy Resources Future*. LC Schwartz, ed. Future Electric Utility Regulation Report No. 2. LBNL-1003797, Lawrence Berkeley National Laboratory, Berkeley, California. Accessed January 14, 2019, available online: http://eta-publications.lbl.gov/sites/default/files/lbnl-1003797.pdf.

Platforms are very often implemented in the form of multiple layers, for the insulation reason stated above. The platform concept can be applied at many scales, from individual software systems up to an entire grid.

A layered platform is a very strong architectural structure that supports future-proofing of grid modernization investments. The layers can even include grid physical infrastructure.

Figure 6 illustrates the use of layering and platform concepts to organize electric infrastructure, sensing, and communications into a platform upon which various distribution applications can run.

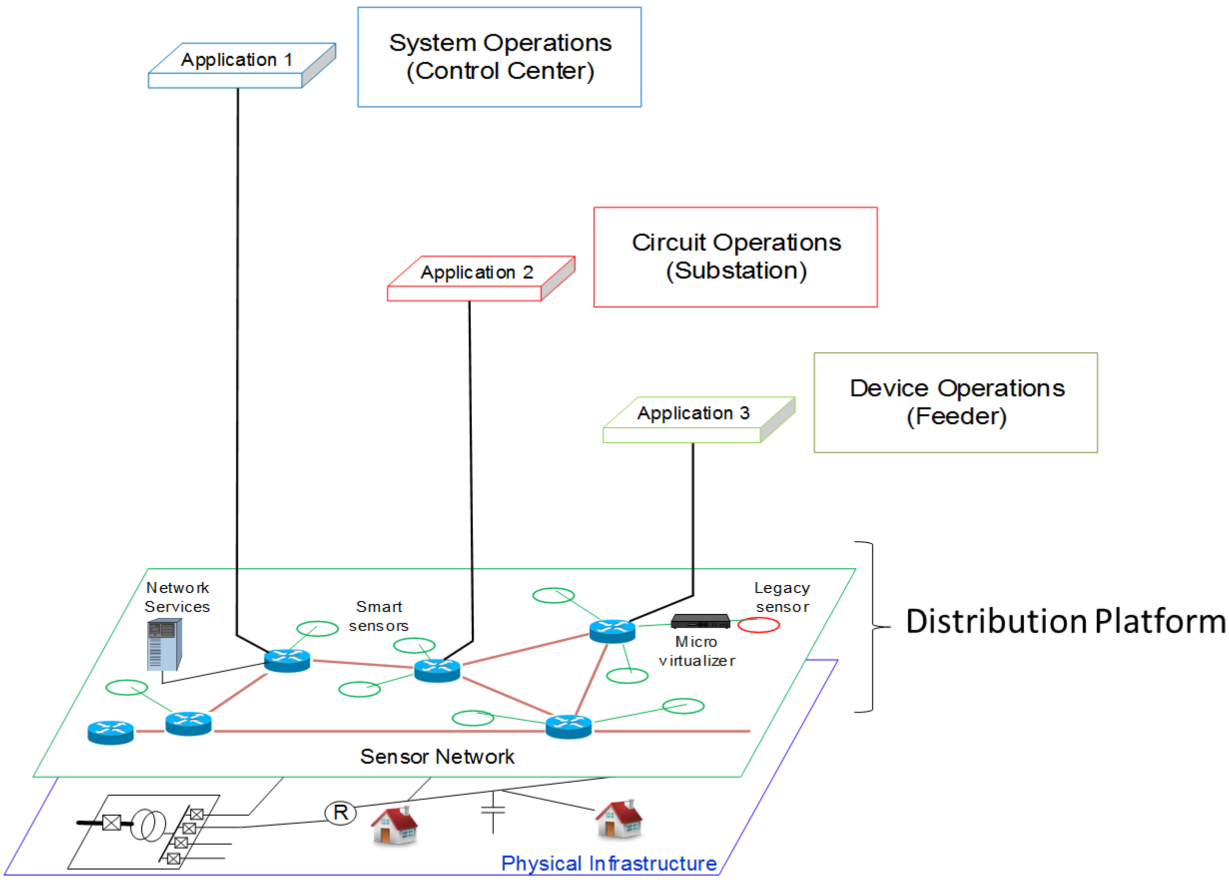

Figure 6. Grid Infrastructure as a Platform Layer

Platform is also a recursive concept, meaning that what is a platform at one level may include many deeper levels that are also viewed as platforms by the layers above. As an example, the hardware in a laptop computer is a platform upon which runs an operating system, which in turn becomes the (two-layer) platform for applications such as word processing, email, and spreadsheets. Looking from the top down, the applications see a platform with well-defined interfaces that supplies a set of computing, memory management, and communications capabilities made available at the operating system level. The operating system sees a set of capabilities for program storage, execution, and data transmission made available at the BIOS level. The BIOS sees a set of hardware components that execute computing instructions, store and retrieve data, and send and receive communication data packets. Each level sees the level below as its platform.

3.3 Multi-Scale Structure

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

Multi-scale structures look very similar at any grid scale when viewed graphically. More deeply, the inherent properties of the structure work the same way at any grid scale. Use of multi-scale structures provides conceptual integrity (making for a good architecture), provides re-usable structure template with known inherent properties, and has inherent structural scalability. Layered decomposition and multi-scale structure are closely related.

3.4 Coordination

Coordination is the means by which a set of decentralized elements cooperate to solve a common problem, thus becoming a distributed system. As a result, coordination structure is a key aspect of distributed systems, distributed control, etc. Grid coordination is the systematic operational alignment of utility and non-utility assets to provide electricity delivery.

Coordination is a multi-scale concept that applies at the regional level (Transmission/Distribution coordination), at the local level, (coordination of distribution grid devices and attached Distributed Energy Resources), and at the micro level (coordination within a microgrid or a building). Coordination structures must include all of the relevant elements and must avoid three pitfalls: tier bypassing, gapping, and hidden coupling.

Tier bypassing occurs when a device, system, or agent at one level of a grid hierarchy connects to, directs, or controls an element more than one tier away.

Gapping occurs when an element of the grid hierarchy does not have a connection to any higher level tier element and so operates in isolation.

Figure 7 illustrates both tier bypassing and gapping in a coordination structure.

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

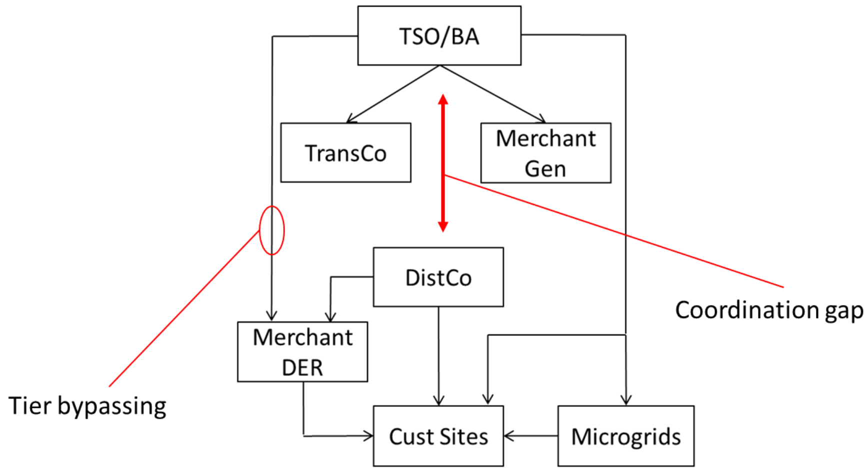

Figure 7. Tier Bypass and Gapping

Coupling occurs when one asset can be controlled by more than one agent. **Hidden coupling** occurs when the structures involved provide control and coordination paths that allow inadvertent coupling. Note that given the nature of electric power systems, some forms of coupling are inevitable. Figure 8 below shows three forms of coupling that can occur due to the connectivity of the electric distribution system. In the leftmost example, poor system design has led to two agents attempting to control the same asset. In the second case, hidden coupling via the distribution circuits has allowed a similar problem to develop (a conflict in terms of voltage regulation on the secondary). In the rightmost example, the coupling is caused by tier bypassing (the Transmission System Operator bypasses the Distribution Operator, causing a conflict in managing distribution reliability).

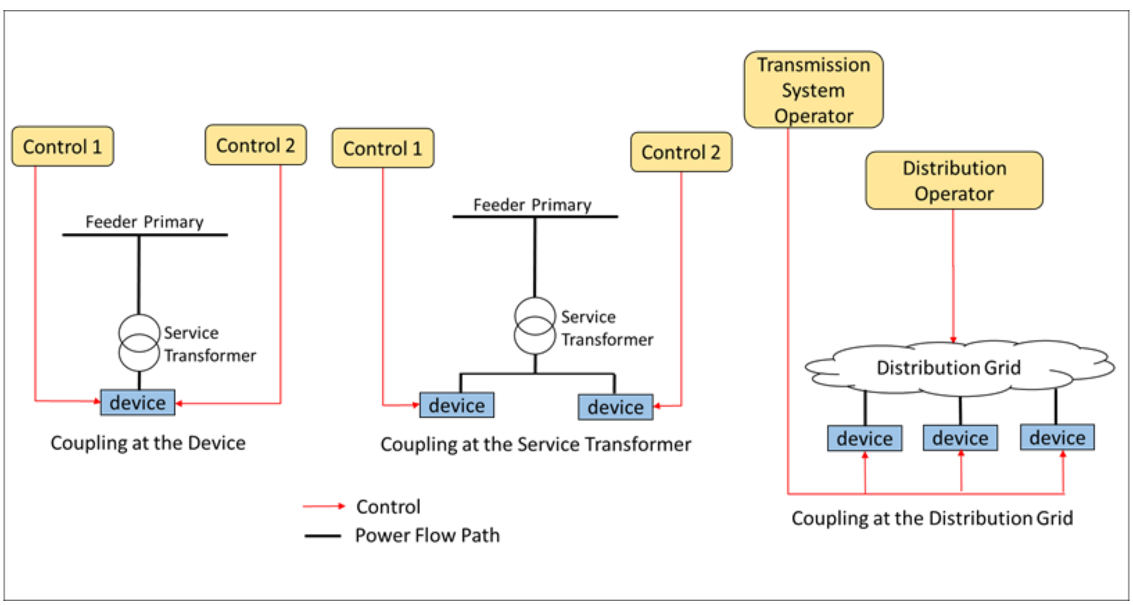

Figure 8. Various Forms of Coupling at the Circuit Level

These issues can be resolved even when physical circuit coupling exists, through careful use of coordination structure and methods.

A well-defined structure for coordination frameworks is the Laminar Network,[1] which derives from the principle of layered decomposition. Note that this is a multi-scale network structure.

3.5 Another Form of Coupling

Figure 9 shows a commonly used structure for electric distribution utility sensing and control.

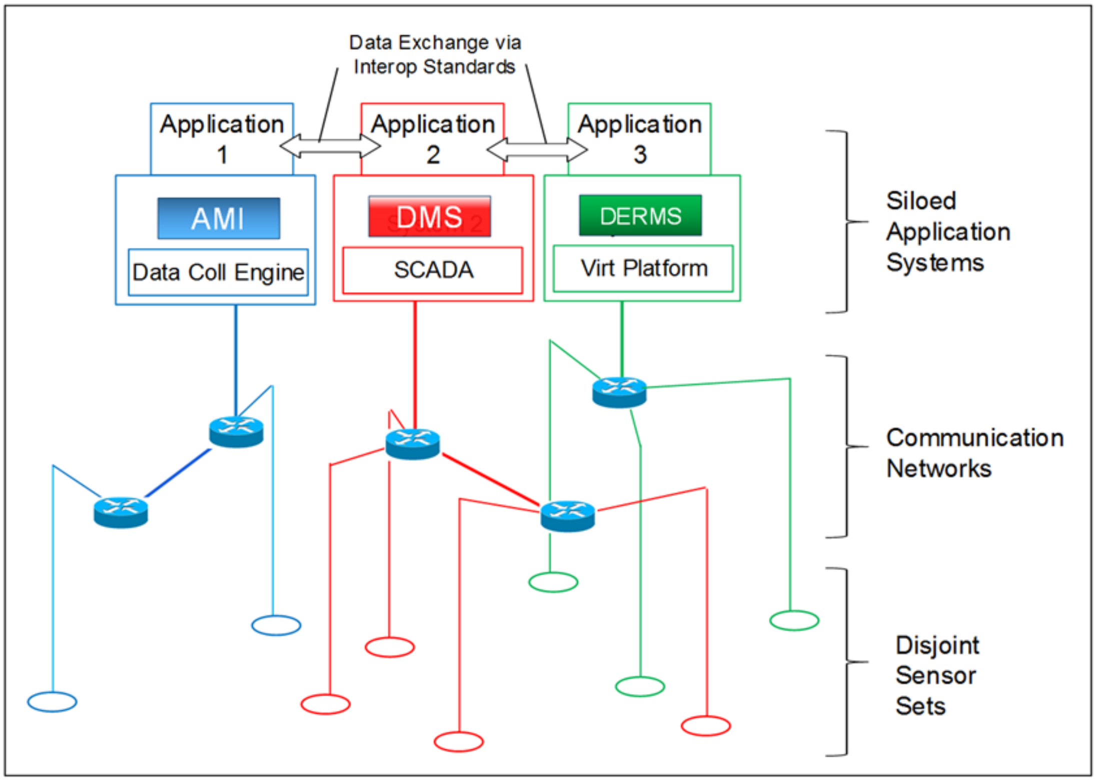

Figure 9. Coupling via Back End Integration

This multiple vertical silo structure is expensive due to back end integration costs, and is anti-resilient due to the back end coupling of applications – failure in one can ripple through to degrade others. It is also anti-extensible, because adding or subtracting applications requires new integration to existing applications. Interoperability efforts have yet to simplify the integration problem and *cannot address the anti-resilience issue, which is fundamental to this structure.* The issue may be resolved through the use of layering and silo-to-layer conversion.

3.6 Buffering in Complex Systems

Buffers are mechanisms for decoupling flow variations, especially random or unpredictable variations. The presence of a buffer provides a system with “springiness” or “sponginess” that makes it resilient to a variety of perturbations. In fact, lack of such springiness is a resilience vulnerability. Most complex systems have some form of buffering: communication systems have “jitter buffers” to even out the flow of data bits in communication network transmission;

[1] JD Taft, Comparative Architecture Analysis: Using Laminar Structure to Unify Multiple Grid Architectures, PNNL-26089, November 2016. Available online: https://gridarchitecture.pnnl.gov/media/advanced/Comparative%20Architecture%20Analysis-Final.pdf

computing systems have various kinds of data buffers that operate on differing time scales; logistics systems have buffers – they are called warehouses; water and gas systems have buffers – they are called storage tanks. In each case, the buffer is some form of storage that evens out irregular flows, thus reducing or eliminating the impact of volatility (fluctuation or interruption) in source or use.

Electric power grids have many systems that can benefit from buffering. These include the communication networks and the information processing systems, and the sensing and control systems. They also include the electric power system infrastructure. Increasing volatility in the grid power flows, caused by addition of variable energy resources, is causing increasing stress in grid operations. Lack of fast, flexible buffering is a factor in the lack of resilience of the grid.

> The use of electric grid energy storage as a core infrastructure component can greatly improve essential grid operations and resilience by supplying the missing buffering.

3.7 Definition Structure

A wide array of concepts must be employed in grid modernization work and the terms used to label them need careful definition. Aside from the obvious criterion that the definitions must be clear, there are actually structural considerations. These are:

1. Orthogonality – definition should not overlap. Overlap causes confusion and makes it very difficult create measures (so-called "metrics") that clearly relate to a specific characteristic of the grid.
2. Deconflation – definitions should not join together multiple issues, for the same reasons as with orthogonality.
3. Relational Structure – recognize that a proper set of definitions consists of not just the basic definitions, but also the relationships among the definitions. In other words, sets of definition have a structure (when done well).

Figure 10 illustrates an example of definition structure.[1]

[1] Grid Architecture team, Grid Characteristics: Using Definitions and Definition Structure for Decision-Making, PNNL-SA-141678, February 2019, available online: https://gridarchitecture.pnnl.gov/media/methods/Grid_Characteristics_Definitions_and_Structure.pdf

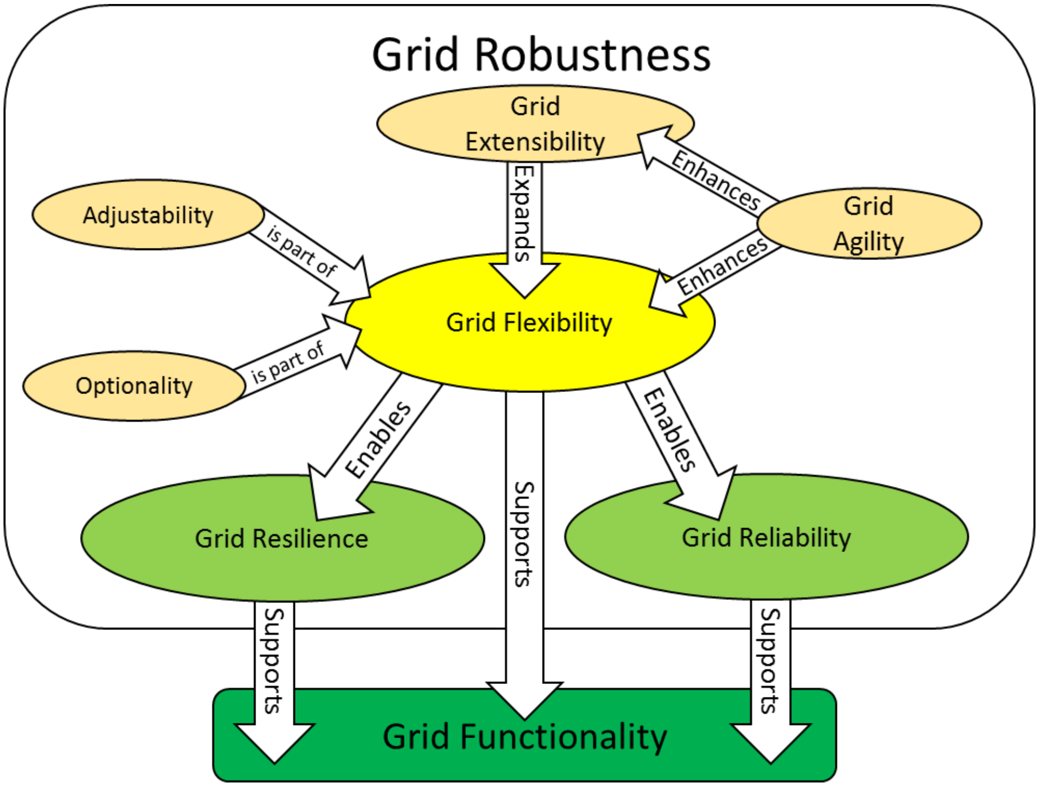

Figure 10. Example Definition Structure

Use of both the well-formed definitions and the definition structure provides a powerful tool for reasoning about grid modernization.

4.0 Final Comments

Grid Architecture is a complex discipline, but it provides many principles and guidelines that can be understood and applied by architects, developers, systems engineers, and regulators without the need to actually become grid architects. Among these are the following:

- Use systemic issues rather than use cases to understand questions regarding grid modernization.
- Layered decomposition and platforming are useful approaches to managing grid complexity and providing future-proofing of grid investments.
- Using the same structure template at different scales (multi-scale structure) provides scalability and resolves complex structure issues in a uniform and consistent way.
- Coordination among the elements of a grid, including non-utility assets, is necessary for a smoothly functioning modern grid. Use layered decomposition and multi-scale structure principles to avoid tier bypass, gapping, and hidden coupling.
- Complex systems need buffering for resilience. Grids are no exception.
- It is not enough to have definitions for key concepts. The definitions should be well formed and should be placed in a structure that shows their relationships. This is a powerful tool for reasoning about grid modernization.

For the grid architect, a deep understanding of these principles is necessary for the development of grid architectures. For the product supplier, an understanding of these principles aids in determining how to specify, structure, and integrate new products for electric power systems. For the regulator, use of these principles can provide considerable insight into grid modernization issues and provide conceptual tools to understand modernization plans and proposals, and how to create guidance to utilities.

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