21, rue d'Artois, F-75008 PARIS
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CIGRE US National Committee
2013 Grid of the Future Symposium

Laminar Control for Distributed Generation and Microgrid Integration

J. TAFT[1]
Cisco Systems, Inc
USA

SUMMARY

The penetration of distributed generation (DG), local energy networks, and microgrids has the potential to cause disruptions in grid operation that have been noted widely in the utility industry. Many of these effects will be felt at the distribution level, but some can reach beyond, and in any event grid control must be considered holistically because these changes have impacts from the system balancing level, down through the Transmission System operator (TSO) and Distribution System Operator (DSO) to prosumers premises. Large penetrations of DG and extensive use of responsive loads have the consequence that distribution cannot be treated as something that passively floats on transmission as has been the practice. Many of the existing control systems were designed under assumptions that are now being violated by the introduction of these new functions and many paradigms for new grid controls do not have the necessary properties to address the key architectural issues that have begun to arise.

Three key properties that are needed in advanced grid control are distribution, coordination, and scalability. The emerging paradigm of Laminar Control can provide these properties, along with ease of legacy system integration and resilience to grid separation and microgrid islanding. In the Laminar Control approach, control is distributed, meaning that elements reside in various locations in the power grid (still including the control center) and these various control elements cooperate in solving the real time grid control problem. Coordination, which involves a "vertical" data flow, keeps the elements focused on the common problem, whereas application level intelligence involves "horizontal" data flows that are a part of the local domain (area, region, etc.) control. This differs from agent-based approaches in terms of providing a structure that inherently facilitates scalability and in terms of providing coordinated control action that can be specified, managed, and analysed. This control paradigm can be applied across the entire power delivery chain, or it can be applied on smaller scales, such as in a single distribution system, or even a single microgrid.

KEYWORDS

Microgrids, distributed generation, grid integration, control

[1] jetaft@cisco.com

LAMINAR CONTROL

Public policy has set the US electric industry on a path towards a hybrid power system increasingly powered by customers' distributed resources. Based on EIA and other credible forecasts, installed DER capacity may reach nearly 30% by 2020 – effectively all the incremental capacity installed over this decade. It is clear that new grid operating systems, described by EPRI as Grid 3.0, are required to enable policy goals

Distributed and hierarchical control methods have been available for decades and in the case of electric power systems, some of these concepts have been used in portions of the grid, but not as an Ultra-Large Scale (ULS) control. By ULS we mean the concept developed at the Software Engineering Institute [1] to describe extremely large, complex systems with the following characteristics:

- Decentralized data, development, and control
- Inherently conflicting diverse requirements
- Continuous (or at least long time scale) evolution and deployment
- Heterogeneous, inconsistent, and changing elements
- Normal failures (failures are expected as a normal part of operation)

In the power grid domain, certain approaches to wide area grid control have employed a single physical variable that presumes to characterize a key aspect of system state. At the transmission and generation level, system frequency is used for this purpose. It is widely used in incremental area balancing via Area Control Error and Automatic Generator Control. System frequency has also been proposed as the basis for control of large number of responsive loads not owned by the electric utility [2]. At the distribution level, feeder voltage is used in Volt/VAr control systems, both in those that act centrally and those that are composed of a collection of independent agents [3]. Such methods have enjoyed a degree of success but encounter difficulties in two areas:

1) Such systems can become unstable due to feedback through the grid itself
2) When multiple functions want to use the same infrastructure for possibly completing or even conflicting purposes, as is happening with distributed energy resources [4], then a single variable is not sufficient to enable proper coordination or federation of the multiple control processes involved

Recently a control framework based on Network Utility Maximization [5] and Layering for Optimization Decomposition [6] has emerged as a distributed paradigm for ultra-large scale controls, especially for power grid control [7]. In this approach, a structured network of optimization nodes communicates hierarchically via scalar signals to cooperate in solving a joint optimal control problem. This layered decomposition can be mapped onto the structure of a physical system such as a power grid to solve the control issues of federation, disaggregation, and constraint fusion while allowing for local "selfish" optimization. This approach is a hybrid of central and decentralized control, made distributed by virtue of the various parts engaging in cooperation to solve a common problem. In the layered decomposition approach, Network Utility Maximization is used to provide overall coordination, with most nodes acting as both a coordinator for sub-problems at the next tier below, and well as a sub-problem solver for the coordinator for the next tier above.

Problems may be decomposed recursively, leading to a multi-layer structure that inherently supports distributed computation. When this type of mapping is done for hierarchical controls, especially for power grids, it leads to a logical data flow structure that has useful characteristics.

There are three principal data flows that matter here:

1. "Vertical" signal exchange among optimization nodes for multi-tier coordination
2. Hub and spoke signal exchange among master and sub-problems nodes for tier level coordination

3. Peer to peer flows within a layer for local cooperation

Figure 1 shows these primary data flows. Note that the first flow in the list is essentially a subset of the second on the list, but it is helpful to consider an entire vertical coordination signal chain as one of the flows. We view this model as having two axes of distributed intelligence and refer to the vertical single flows and optimization chain as *coordination distributed intelligence*, and the tier hub-and spoke and peer-to peer interactions *as application distributed intelligence*. The overall vertical flow across all tiers with optimization node operation is denoted as *Deep Area Coordination* (DAC). We refer to the entire architecture as *Laminar Control*.

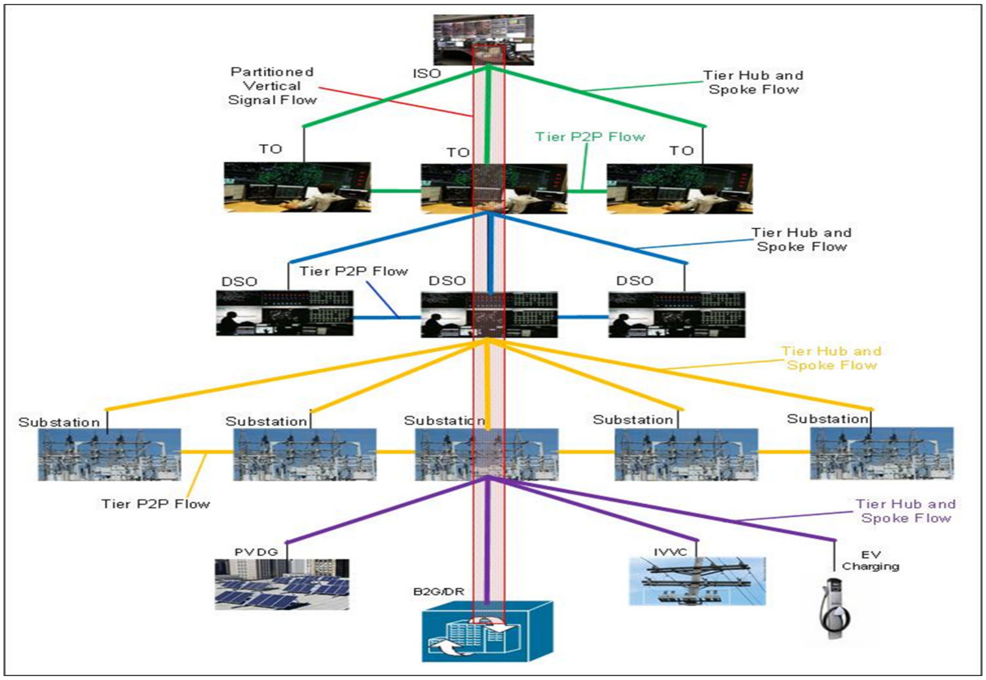

Figure 1 Laminar Control Mapping and Key Data Flows

Note that we decompose the optimization problem by tiers that match physical power grid tiers. In addition, the elements are broken up at each tier into domains, with the definition of domain depending on the level in the power grid hierarchy. Domain definition is flexible to give the system designer freedom. At each domain in the logical control architecture, there is a computational element that solves the optimization problem for that domain, which means that in general each domain optimizer simultaneously acts as a sub-problem solver for the level above and as a master solver for the level below. Adding tier coordination functions to the vertical signal flows leads to a simple coordinator for each node, where the optimizations are calculated and orchestration for the sub-tier is handled. Figure 2 illustrates a domain and coordinator structure. Note that within each domain, conventional control loops and sequential logic exist, but now traditional central SCADA is replaced with distributed layered optimization processes running in the domain coordinator. This mechanism allows for both control federation and command/dispatch disaggregation. The use of local state, constraints, and optimization functions provides for “selfish” optimization, which is how local conditions are handled and how organization and system border deference is established.

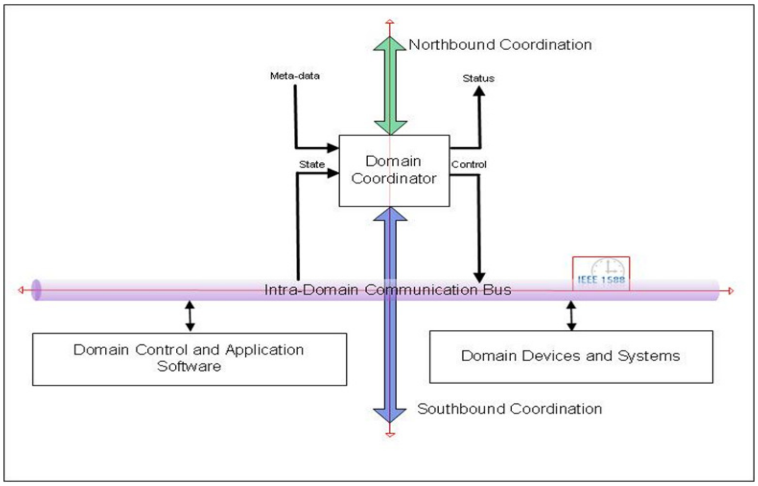

Figure 2 Domain and Coordinator Structure

In a Laminar Control architecture, each optimization layer node except for the very top and the very bottom has two parts: a northbound portion that solves a sub-problem element for the master problem residing one layer up, and a southbound portion that acts as the master for the decomposition of the current layer sub-problem into a new master and set of secondary sub-problems.

One significance of this structure is that signals flowing between southbound master and northbound sub-problem are confined to the two-half layers involved, meaning that such signals do not aggregate in the communications sense when moving up the coordination node stack. This is therefore an automatic mechanism for preventing the top level data pipe bandwidth requirement from growing without bound as the control system scales upward in size. At each level, the number of signals involved depends on the number of defined sub-problem elements. It is always possible to define additional domains as necessary, thus controlling the southbound "fan-out" from master to sub-problem set at the cost of increasing slightly the fan-out of the layer above. Note that the fan-in at the top of each layer is one except for the very top node, which has a fan-in of zero.

In the Laminar model, master problems and sub-problems exchange the information necessary to solve the layered optimization problem in a lightweight manner. In other words the coordination signal generation process effectively encodes information about the control problem, the system state, and the constraints.

We can take advantage of this property in two ways:

1. The amount of data that must be passed from level to level in the control hierarchy can be limited to just the coordination signals, thus greatly limiting the necessary bandwidth of the inter-layer communication links.
2. Power state can be determined in a distributed fashion and on a local domain basis, which eliminates the need to determine and distribute state globally, thus reducing computation complexity and bandwidth requirements by employing multiple smaller distributed data acquisition and state calculation processes and limiting state distribution.

Both of these consequences are important to obtaining a distributed control system implementation that scales automatically as it is rolled out in an incremental fashion.

Another way to look at Laminar control networks is that they are (or can be designed to be) self-similar, a property that manifests itself when we consider the hub-and spoke traffic pattern at various level in the hierarchy. Self-similarity [8] is a geometric property whereby a whole object is similar in shape to any of its parts. An example would be a complex leaf made up of leaflets of the same shape as the overall shape of the complex leaf. This allows us to think about the data flow traffic patterns in a unified way at any level in the power grid hierarchy, which is an aid to selecting and configuring communication network protocols and communication network Quality of Service measures.

With this property, we may view the partitioned grid state elements residing in the domains at each tier as a multi-resolution representation of state. This issue is important because it leads to powerful scalability properties that become crucial in advanced grid environments where very large volumes of data must flow from millions or tens of millions of endpoint devices and where communication link failures are common, as is the case with ULS systems

ROBUSTNESS AND MICROGRID/DG INTEGRATION

In control engineering, there is a class of design methods labeled *robust* (the H_2-H_∞ controller designs [9]) that are relatively insensitive to uncertainty and variation in the parameters of the model of the system being controlled. Some view such methods as "hardening" in the sense that they can tolerate a degree of stress but will fail (perhaps catastrophically) when the stress becomes extreme enough.

More recently, the concept of anti-fragility has been introduced and has become linked to the term resilience [10]. In control engineering, resilience has been a topic of attention for some years and has resulted in an evolving series of definitions, including [11]:

"*Resilient control systems are those that tolerate fluctuations via their structure, design parameters, control structure and control parameters*".

More recent definitions also address the element of security by including the response of the system to malicious attack as well as the fluctuations just mentioned. The anti-fragile concept suggests that such systems not only tolerate stressful random fluctuations, but may actually improve as a result of encountering them. In the case of Laminar control systems, another capability not strictly indicated by data flow issues but nonetheless existent, is the manner in which it can handle microgrid islanding.

Microgrids are becoming recognized as a means to address overall grid resilience by taking advantage of distributed generation to supply local energy needs, with the main power grid as one input and/or backup. While in some cases this is viewed as a means of becoming less dependent on main power grids, it is also viewed as a potential means to enhance power system reliability. Much effort has been devoted to the detection of microgrid islanding, but the actual coordination of microgrid operation with main grid operation has not been resolved. The control architecture discussed in this paper provides the means to do this coordination in a manner that works equally well on either side of the microgrid point of common connection.

Understanding how this works requires the introduction of some additional aspects of how Laminar Control is to be implemented in practice. When a section of the Laminar Control tree (be it microgrid or circuit section) becomes islanded, two additional modes of operation are available:

1) the islanded microgrid or isolated circuit section uses its local optimization criteria and local grid state to operate in a manner that adapts to changing local conditions, rather than just continuing on the basis of the last command/information from a supervisory system that is no longer connected to the island; in effect it becomes a mini-system all its own, performing coordination within the domain of the islanded portion as it if were a complete system
2) the islanded microgrid or circuit section also can seek a different master control node and rejoin the control chain through that node if communication network connectivity permits, in which case the new master will automatically adapt to its expanded set of sub-problem nodes

This means that a customer microgrid or utility microgrid would seamlessly and automatically reconnect to an alternative circuit or generation source as they may become available following an area outage as experienced during recent super storms. If we take these capabilities of Laminar Control into account, we see that such control systems may in fact be more than just robust. The same comments apply to DG and local energy networks.

CONCLUSIONS
Laminar Control addresses EPRI's Grid 3.0 requirements by providing both a) solution for ultra-large scale controls needed at the expected adoption of distributed energy resources globally and b) an effective architecture to manage the transition distribution networks from legacy one-way infrastructure to modern multi-way systems. Laminar Control has unique structural properties and available modes of operation that go beyond the issues of federation, disaggregation, and constraint fusion. These properties may make it possible to provide scalability, enhanced network security, resilience, and management of system and operational complexity, all of which are quite valuable in practical implementations across an evolving power system.

Likewise, the modular structure lends itself to discrete capital investments to keep pace with DER adoption. The additional advanced technology/distributed controls overlay on a new modern grid infrastructure (platform) installed when replacing aging infrastructure. Such a core platform includes an enabling field area communications network as well as a transition from analog to digital protection relays and distribution grid designs that bear resemblance an electrical bus as opposed to traditional large-to-small wire. This allows utilities to plan investments along a 3-prong approach:

- Address immediate reliability gaps
- Invest in grid modernization as capital budget allows
- Invest in an overlay of advanced technology as DER adoption increases

Modularity, scalability, resilience are key attributes of systems that will necessarily evolve with the changing pace and shape of electric industry transformation. Laminar Control in this context offers utilities, policy makers, technology firms and others a very effective, lower risk architectural approach for the future of distribution.

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