21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2012 Grid of the Future Symposium

Modern Grid Control Architecture

J. TAFT[1] **P. DE MARTINI**
Cisco Systems, Inc **Caltech Resnick Institute**
USA

SUMMARY

Electric power grids are becoming stressed by integration of intermittent renewable resources and significant adoption of distributed energy resources. The complexity of the grid is growing rapidly as we attempt to support technical, business, and societal goals for which power grids were not originally designed. Today, we largely take stability of the grid for granted. However, stability could collapse because of new dynamics introduced to the grid, and because the extreme complexity makes traditional control analysis intractable, so that grid behavior is more unpredictable. To ensure grid stability and have the agility to remain reliable under highly dynamic destabilizing conditions requires that grid control systems also evolve in ways that address these new changes and the resultant operational problems. Ultra-large power system control architecture - a macro architecture for grid control that can solve the problems inherent in the present power grid evolutionary path is needed and has not been addressed in present smart grid architecture efforts.

In the absence of this control architecture, transmission and distribution owners are applying patch-fix controls in an ad hoc fashion to address serial requests for resource interconnection and demand-side programs. This ad hoc approach is creating discontinuities in interoperability standards and context voids in smart grid reference architecture efforts. The lack of true vendor-to-vendor interoperability is exacerbating the situation. The architectural exigencies are resulting in an emerging chaos in the grid control system macro-framework that is unsustainable and inherently unsecure on several dimensions. The industry is still at the piloting and experimental stage, so there is time to address the issue before significant investments are made that would commit utilities to an architectural approach that is severely problematic at full scale.

Considerable progress is being made in the grid control research community in terms of progression from traditional grid control configurations to advanced control architectures that provide the ultra-large scale structure to handle multi-objective, multi-constraint grid control problems in a framework that can support coordinated control across utility organizational boundaries and, potentially, prosumer premises. Such a framework can preserve stability while solving the hidden coupling problem, the control federation problem and the tier disaggregation problem. The keys to this approach are three-fold: rectify the macro-structure of grid control to eliminate the emerging chaos; introduce two-axis distributed control; apply multi-level hierarchical optimization tools to grid control design. This paper describes emerging issues in grid control and provides reasons why the present path of grid control evolution is problematic and presents an ultra-large scale architecture for grid control that can solve today's problems and those expected over the next 30 years.

---

[1] jetaft@cisco.com

KEYWORDS

Controls, Architecture, Reliability,

The Importance of a Control Point of View

The electric utility industry has been transitioning for over 30 years in terms of increasing diversity and distribution of resources. The positive results are environmentally cleaner resources, better utilization of the grid and more efficient use of electricity by customers. However, as a consequence the grid has become increasingly complex and stressed by the variability that has been introduced by intermittent wind and solar photovoltaic (solar PV) resources and expected with millions of distributed energy resources. Over the past decade considerable research and architectural development has resulted in a set of architectural principals and reference architectures to address the needs of a modern grid – the smart grid.[1],[2] These initial efforts were largely based on the premise of applying information and telecommunication architectural and design approaches as an overlay on the physical grid operations – with a particular focus on information flows to encourage customer response to time differentiated rates to encourage reduction of peak demand and energy conservation. Later, organized markets began to offer customers opportunities to bid their load directly. This convergence of information technology (ICT) and energy technology (ET) that comprises the power grid in this context was the basis for a smart grid.

Much of this architectural foundation was conceived in the early 2000s before social networks and smart phones were launched. Also, with much of the early focus on customer information interactions and relatively modest adoption of distributed energy resources until relatively recently, many of the physical intermittent renewable generation integration issues were focused at transmission level and most of the customer responsive demand was not tightly linked into real-time control of the grid. Now it has become imperative to address the practical architectural and engineering issues related to modernizing a grid to support the scale and scope of the resources envisioned in existing legislative and regulatory mandates in many parts of the developed world. A modern grid [3] needs the following attributes:

- **Observable** – able to determine extended grid state from a set of measurements
- **Controllable** – able to reach any desired status in response to demands of consumers and other allowable control inputs
- **Automated** – intelligent autonomous control functions with human supervision
- **Transactive** – customer and merchant DER devices and systems (non-utility assets) participate in markets and grid operations
- **Secure** – integrated multi-faceted security supporting the first four attributes

Note that three of these five terms are technical terms from control engineering. This is no accident. The structural aspects of the entire power delivery chain and the means by which business outcomes are produced with this structure lead naturally and inevitably to a focus on grid decision and control processes and systems. Smart grid architectures that do not consider the control architectural elements discussed in this paper will not scale to support the energy policy mandates already in place.

As such, the new architectural design thesis for future grids is:

> *Given highly volatile and dispersed resources and physical constraints across the grid, provide a unified multi-tier control schema that simultaneously optimizes operation across all parts of the power delivery system, from the markets, balancing and operational levels to the transactive and prosumer level.*

Emerging Chaos

The complexity of grid operation and control is mounting up and management of this complexity is becoming a serious issue, as traditional design methods become less and less capable of solving the problems in a reliable and predictable manner. Figure 1 below shows the emerging complexity of system interactions with new market participants, increasing interdependency between distribution and transmission operations and points to the need for approaches to grid control that inherently support complexity management. The diagram is complex, but we can easily make a few key observations. Traditional control (black lines) has been well organized from a structural standpoint, despite lack of closed loops in some places, and lack of inter-tier control in some places. Red lines represent mostly newer ad hoc controls, although in at least one case (distribution SCADA) the curved red line has been used as a matter of practical necessity. Most of the curved red lines are relatively new and represent controls that bypass one or more tiers in the grid hierarchy. Power and energy markets are an integral part of the grid control framework.

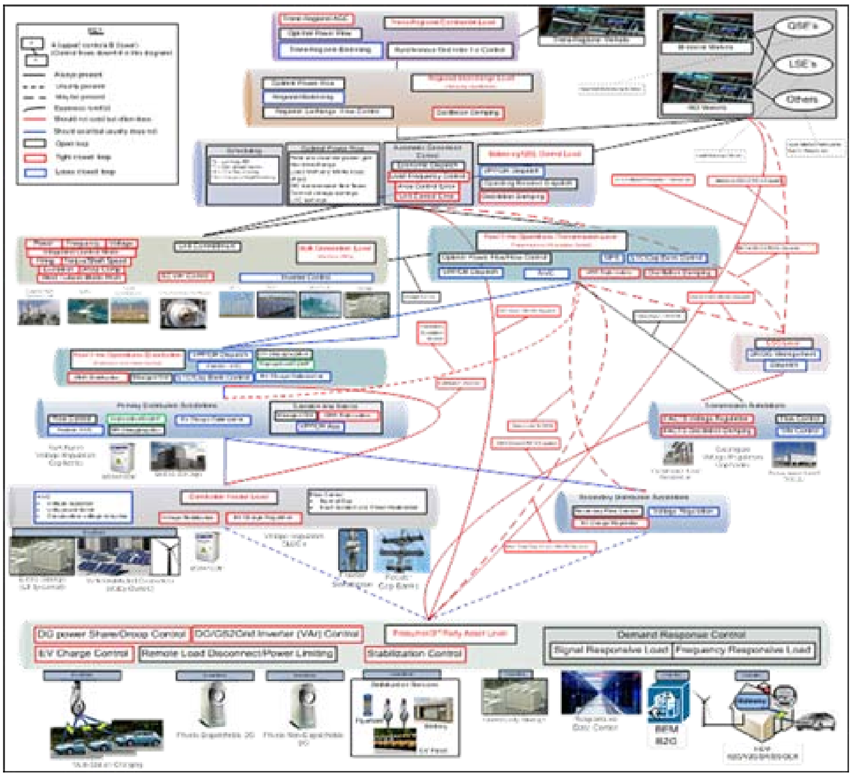

Figure 1. Ad Hoc Macro Grid Control Reference Framework

The curved red lines and ad hoc nested closed loops represent emerging architectural chaos in grid control. The emerging chaotic structure effectively prevents control federation, so that resolving hidden coupling issues and preventing multi-objective clashes is quite difficult. The emerging chaotic structure also effectively prevents disaggregation, so that taking into account local tier conditions and grid state so as to maintain grid manageability at all levels is effectively prevented. Adding new closed loops without a well-defined control framework introduces new opportunities for feedback-based oscillations or runaways, such as with market flash crashes and both price and power grid instabilities. Lack of a regular well-structured framework for control greatly limits both introduction of new capabilities and the ability to modify or solve problems with already deployed capabilities. These points are important because they lead to loss of future opportunities, stranding of assets, and reductions in achievable reliability and robustness of the grid. Since this emerging problem is structural and of ultra-large scale, it will become quite difficult to mitigate should these ad hoc control paths become ossified through deployments and usage at scale.

Principles for a Modern Grid Architecture

It is clear that the present control approaches involve multi-objective, multi-controller structures, and “hidden” interactions through the grid, it is quite possible for such a system to have objectives that compete or even conflict with each other over control of the same grid variables or resources. It is also clear that it is becoming necessary to provide a means for coordinating controls at various levels of the power delivery chain, spanning dispatch/balancing, bulk and distributed generation, transmission, distribution, and responsive load (customer premises or assets) levels. This does not mean that there should be one giant central control system; this is not feasible for many reasons. It does mean that macro control architecture should begin to embody certain architectural principles across these tiers, and to avoid ad hoc control architectures. The architectural principles that must be employed in control design for the grid of the future include the following:

Federation – Modern grid control systems must support multiple objectives. It is, therefore, necessary for the grid control macro architecture to provide an inherent mechanism for support of federation of the controls so that they work in a coordinated fashion, as opposed to clashing, while retaining a significant degree of internal autonomy. This mechanism must be able to work across both system boundaries and organizational boundaries.

Disaggregation – Macro-level commands, such as for a large amount of demand response to be achieved over a service area, must be decomposable to appropriate pieces at each succeeding level of the grid hierarchy until reaching endpoints. This is so that each level can apply constraints visible at that level to maintain grid manageability at all levels and across system and organizational boundaries. Such a capability is needed to support the concept of federation.

Constraint fusion – New control functions involve a great many constraints, often differing at various levels in the hierarchy, so the macro control architecture must support a means to fuse complex and wire-ranging constraints into control solutions.

Robustness – Many closed loop controls used in grid control are PI (proportional-integral) controls. As the complexity of grid closed loop control problems (regulation and stabilization, for example) increases, more robust and adaptive means of control, such as H_2/H_∞ control [4], adaptive critic network control [5], etc. must be supportable.

Agility – Grids of the future will undergo almost continual evolution, as well as experiencing wide dynamic power state variations and various failures. Control systems must be capable of a good degree of dynamic adaptability in both reaction to normal operating conditions in a world of stochastic generation, responsive loads, and market interactions, but also in a world where maintenance of normal operation is desired and expected in spite of device and subsystem failures. Flow reconfiguration, stabilization and regulation across discontinuous failure events, and tolerance of unpredictable market behavior are all necessary.

Ultra-Large Scale Control Architecture

The architectural reference model for future grids also needs to be reconsidered. Over the past decade, smart grid architectures were largely based on the theory of System of Systems (SoS)[6]. The SoS approach treats complexity in terms of a collection of systems, which in themselves combine form a much larger system. This approach made sense in the context of resolving information flows across multiple tiers and parties utilizing services as employed in enterprise software. However, to deal with a modern grid at scale, we must go beyond concepts such as System of Systems and make use of the concept of Ultra-Large Scale Systems (ULS) [7]. This is because the SoS approach does not fully account for the issues that arise for smart grid design where there is a convergence of four very different networks, spanning multiple business entities. Consider the key characteristics of an ultra large scale system in relation to power grids:

- 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)

Using the ULS paradigm, we must consider the macro-scale control architecture of the entire power delivery chain, from balancing to customer owned DER endpoint. We must also consider the multisystem and multi-organizational nature of the full power grid, understanding that different parts of the grid are owned and operated by different parties; even within a vertically integrated utility there are organizational and system boundaries to consider. Long deployment time scales mean that variable topology architectures must be possible while build-outs proceed and transitions are made. ULS contemplates these issues whereas SoS (especially as implemented via Service Oriented Architecture or SOA methods) does not.

Finally, we must apply design and implementation methods powerful enough to solve the control problem in this complex environment. Traditional grid control has many parts, some using feedback in closed loops; other parts operating in open loop mode. Some grid control problems are solved using optimization techniques; others are solved using traditional control engineering or ad hoc methods. A look at emerging trends for power grids shows that traditional control method and structures are becoming inadequate for the power grid of the future. Addressing these issues involves three major elements:

1. Regularizing the macro structure of grid control
2. Implement measurement and control in a two axis distributed form: intra-tier or horizontal and inter-tier or vertical
3. Applying newer methods to design of control systems for the grid

Multi-layer Optimization

The control problem formulations can cover all aspects of grid flow control, regulation, stabilization, and synchronization, charge management, and loss management for as many grid segments and devices as needed as computing scalability is assured structurally. By using the layered decomposition technique along with the virtual mapping strategy, it is possible to avoid the problem of having any given optimization problem grow too large for computation in practical time frames. While the two major methods of decomposition are primal and dual, there are in fact many additional degrees of freedom in this layering approach. Each layer requires the use of a utility function, and includes the means to append complicated constraints to the core optimization problem. In all there are at least a dozen variants on the structure and details of the decomposition.

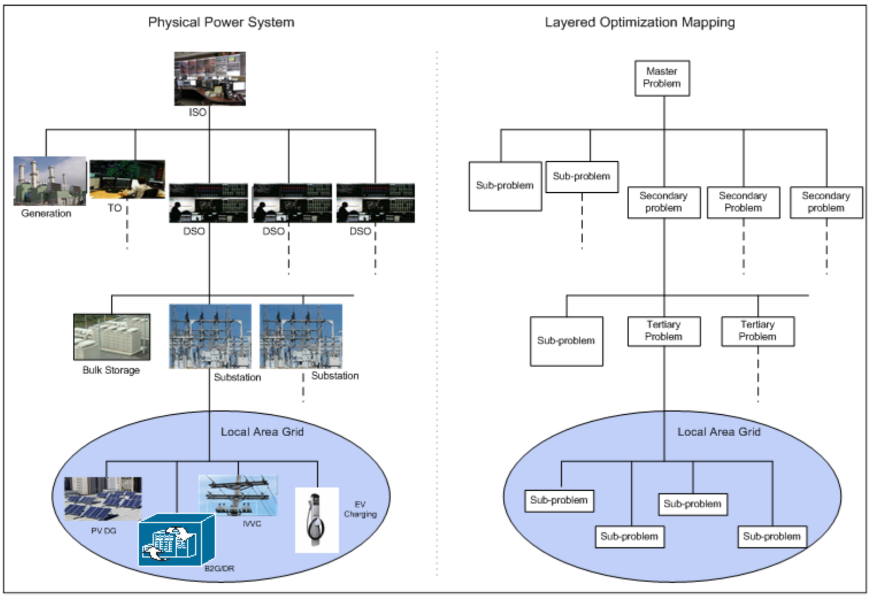

Figure 2. Example Mapping of Optimization Layers onto Power System Infrastructure

At each level in the multi-layer optimization, the appropriate organization, system, or device solves its own optimization problem, but in accordance with signaling from the next upper layer in the form of resource allocations or price signals. Therefore, at each layer there is autonomy of function within bounds that ensure stability and security for the system as a whole. Each device, system, or organization may therefore optimize “selfishly”, but in a fashion coordinated with peers and system level function. Each device, system, organization may decompose its optimization problem into a further layer beneath so that it can provide guidance to lower layer devices, systems, and organization, which are again performing their own “selfish” optimizations.

In addition, the approach is modular so that it can be implemented in stages at any level and a layer interface can be created at any system or organizational boundary. Finally, this framework provides the means to properly integrate new functionality in a rational way and enables both centralized and distributed implementations. For example, local area grid operations such as management of DER, feeder regulation and stabilization, and loss management can be implemented at the primary substation level, including, if desired, a form of local area power market. In this manner, the entire control architecture can provide the key capabilities needed in the ultra-large scale grid control framework: federation, aggregation, constraint fusion, and robustness.

Conclusion

The scale and scope of the grid as described above is vastly more complex than the existing electric system – which has been described as the largest and most complex machine on earth. It is important to remember that the electric grid is a critical infrastructure that provides an economic backbone for modern economies. As such, developed economies are not tolerant of grid disruptions. Likewise, failure to achieve existing policy mandates related to renewable and distributed resources is also not acceptable. Therefore, a unified multi-tier control schema that simultaneously optimizes operation across markets, balancing, operational and transactive customer levels is required.

This modern grid control architectural framework provides the means to integrate distributed markets as grid control elements without the need to try to close large loops around multiple tiers of the power delivery system. The layered optimization decomposition approach, when combined with the concept of vertical and horizontal distributed intelligence and control and framework regularization yields:

- Clean control framework for the entire power delivery system that eliminates chaos
- Enable new complex functions and constraints while maintaining system stability and security
- Control coordination at multiple levels while enabling each level to operate in a manner based on local tier level requirements and constraints
- Enable any tier level control to provide coordination signals to devices, systems, and organizations at lower tiers and to accepts such coordination from tiers above
- Framework that provides the means to integrate third party (non-utility) interaction with grid control in an operationally non-disruptive manner.

BIBLIOGRAPHY

[1] GridWise Architecture Council, GridWise® Interoperability Context-Setting Framework, US Department of Energy, March 2008

[2] Smart Grid Interoperability Panel, Smart Grid Conceptual Model v1.0, National Institute of Standards & Technology, April 2010

[3] United States Congress, 2007 Energy Independence & Security Act, Title XIII – Smart Grid, Section 1301 - Statement of Policy on Modernization of Electricity Grid.”

[4] Goncalves, et al, Multi-Objective Optimization Applied to Robust H2/H∞ State Feedback Control Synthesis, Proceedings of the 2004 Control Conference, Boston, MA, 2004

[5] Jiaqi Liang, Ganesh K. Venayagamoorthy, and Ronald G. Harley, Wide-Area Measurement Based Dynamic Stochastic Optimal power Flow Control for Smart Grids with High V~~v~~ariability and Uncertainty, IEEE Trans. on Smart Grid, March 2012, pp. 59-69

[6] Dahmaan, J., Rebovich, G., et al, Systems Engineering Guide for Systems of Systems, US Department of Defense, August 2008

[7] Peter Feiler, John Goodenough, et al, Ultra-Large-Scale Systems The Software Challenge of the Future, Software Engineering Institute, June 2006