# Ultra Large-Scale Power System Control Architecture

### A Strategic Framework for Integrating Advanced Grid Functionality


## Connected Energy Networks Business Unit

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## Introduction

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. 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. Current power system controls do not address the grid requirements to achieve existing policy mandates for renewable and distributed resources, and responsive customer demand. An ultra-large scale power system control architecture - a macro architecture for grid control that can solve the problems inherent in the power grid's evolutionary path is needed and has not been addressed in present smart grid architecture efforts.

Today, 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 acerbating the situation. This architectural exigency is resulting in an emerging chaos in grid control system macro-architecture 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. Failure to address these issues will result in rapidly escalating system deployment and maintenance costs, potential stranded assets related to replacement of the "ad hoc" systems, along with substantial operational risks that are unacceptable under current utility and regulatory practice.

## 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 (DER). It is important to recognize that that the sum of multiple random variable sources on the grid, such as transmission connected wind and solar PV does not even out the power flow because there is no grid "averaging" or "low pass" function as yet. In stochastic systems the sum of two or more random variables is still a random variable. This is different than the dampening effect that occurs with bulk system operational methods managing aggregate supply and demand which does dampen the effects of variability from individual distributed resources and customer loads. However, on distribution the same challenge of multiple random variables still result in random variables that can cause significant power quality and stability issues. Such variability in generation is among the many new potential causes of grid instability that lead to the need for a new macro scale control architecture for modern grids.

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.[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.[3]

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 variable energy resource (VER), such as wind, 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. In essence, the modern grid design brief has changed. It has become clear that we must address the integration of the following four networks:

1. Power grid (ET) with its inviolable set of physical rules

[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] US DoE definition: "Smart grid" generally refers to a class of two-way communication and computer processing technology used to bring utility electricity delivery systems into the 21st century.

2. Information and communication networks
3. Markets, especially participation of prosumers [4] and merchant-provided DER services
4. Social networks as grids become interactive with customers and their smart devices

U.S. policy is to allow owners of distributed resources to effectively and reliably provide their services at scale, and operate harmoniously on an interconnected distribution and transmission grid.[5] At scale, DER markets and pricing mechanisms can have a material effect on grid stability and reliability as visible or hidden elements that are tightly coupled within a closed loop of a distribution control system managing reliability and power quality. Market design is an essential element in grid control architectures for a future with significant distributed resources.

Social networks have three properties that will increasingly exert influence on the grid operations; Small-world Phenomenon, Social Contagion and Reflexivity. Small world phenomenon relates to the short chains of interpersonal relationships that connect us. Facebook's research in 2011 suggests there are less than five degrees of separation among us. These relationships can be leveraged for social energy applications that use peer pressure to encourage people to track, and ultimately reduce, energy use in the home.[6] Social contagion is the concept of ideas or actions spreading like a virus among a community of people. The research is not conclusive on the similarity to biological contagions; however, the potential for coordinated social response is very real possibility as demonstrated by Earth Hour's annual Earth Day lights out event.[7] While this event is a positive activity, the threat of coordinated negative virtual social action is also real, particularly as we evolve over this decade with networked machine-to-machine interactions, such that turning lights off is a "Siri" command away. Reflexivity relates to positive and negative feedback increasing magnitude of action and reaction within social network. The issue is the potential to have increased real-time market price volatility caused by automated "program trading" by customer and aggregator energy management systems which may also cause significant power flow variations and instability/power quality issues on related distribution and regional transmission systems. Clearly, the convergence of the third and fourth networks with power grids via ICT triggers the need to reconsider existing control architectures, market designs and business models.[8]

As such, the convergence of the electric grid with ICT, markets and social networks requires this modern grid[9] to have 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

[4] Prosumer refers to an electric customer that consumes energy from the grid as well as produces power from onsite generation (solar PV, fuel cell, etc.) that feeds back into the grid.
[5] United States Congress, 2007 Energy Independence & Security Act, Title XIII – Smart Grid, Section 1301 - Statement of Policy on Modernization of Electricity Grid."
[6] Facebook, Opower and the National Resources Defense Council jointly released a social energy application in April 2012
[7] In 2007, Energy Australia measured a demand reduction of over a 10%
[8] De Martini, P., and von Prellwitz, L., Gridonomics™, Cisco Systems, 2011, available online
[9] National Energy Technology Lab, Modern Grid Strategy: Smart Grid Concepts presentation, US DoE, September 2009

- 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. We recognize the importance of security in grid control architectures and the fine work of organizations like the International Society of Automation's ISA99 Committee[10], North American Electric Reliability Corporation and several Federal and state agencies addressing existing control system security issues and standards. This paper does not address security in depth as Cisco grid cybersecurity papers[11,12,13] and others referenced in this paper discuss the topic at length.

Efforts to create reference "smart grid" architectures have been based largely on enterprise IT principles rather than control systems paradigms, and so do not provided the necessary framework for convergence of all four of these networks. Without consideration of the control architectural elements discussed in this paper, the grid of the future will not scale to support the 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 Trends in Grid Operations

As a starting point, it is important to understand in more detail the changing service requirements for electric grids under the current utility industry transition.[14] The following three issues highlight the significance of the changes on current control and operational systems.

A consequence of the retirement of older fossil fueled generating resources and increase of VER/DER resources as part of the portfolio may result in a net decrease of rotational inertia and therefore grid stability. This is particularly problematic in areas with remote wind and solar PV resources and retirement of large steam turbine based generation near load centers. This reinforces the need for algorithms for fast dynamical control to ensure grid stabilization at both transmission and distribution levels.

Also, the concept of transactive control where customer premises may interact with energy and power markets on a programmed basis puts those markets into the control loops. This raises two issues: one is that price responsive loads may cause price and grid instability[15,16] and the second is that they may cause

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[10] ISA99 Industrial Automation and Control Systems Security Committee: http://isa99.isa.org/ISA99%20Wiki/Home.aspx
[11] Cisco, Cisco Connected Grid Security for Field Area Network, 2012, available online
[12] Cisco, Securing the Smart Grid, 2009, available online
[13] Cisco, Securing SCADA Protocols for NERC CIP, 2012, available online
[14] De Martini, P., Future of Distribution, Edison Electric Institute, July 2012, available online
[15] Roozbehani, M., et al, Volatility of Power Grids under Real-Time Pricing, MIT, 2011, available online
[16] Wang, G., et al, Real-time Prices in an Entropic Grid, University of Illinois, Urbana-Champaign, 2011, available online

"flash crashes" in the energy and power markets, in a fashion similar to what can happen in the stock markets with programmed trading. Ordinary grid control systems and design methods do not address such issues, which can involve high-complexity nonlinear systems.

Much has been written about the problems that arise in power grids due to reverse power flows and other behavior caused by various subsystem interactions and by use of the grid in ways not foreseen when the grids were designed.[17] These include unfortunate interactions of Volt/VAr control and demand response[18], control mis-operation[19], and the previously referenced issue of energy market destabilization by responsive loads. The net result of these emerging trends is that older control systems do not have the capability to manage the grid properly when penetration of variable distribution resources reach levels envisioned in public policy. It is quite possible for smaller scale adoption of DER on a circuit work adequately, but only reveals the real problems after larger penetration levels have been reached.

To address these and other issues, grid owners and operators are being asked to provide capabilities that were not contemplated when the grids and their protection and control systems were originally designed. These newer functions are well-known and include such items as:

- VER integration (transmission level)
- Wide area measurement, protection, and closed loop control
- DER integration (distribution level)
- Energy storage integration
- Responsive loads (command, price, and /or system frequency)
- Integrated Volt/VAr control
- Advanced distribution fault isolation/service restoration
- Electric Vehicle (EV) charge management
- Third party energy services integration
- Inverter control for fast VAr regulation
- Local area grid and microgrid power balance and flow control
- Multi-tier virtual power plants
- Energy/power market interactions for prosumers
- Electronic grid stabilization (FACTS for transmission; DSTATCOM for distribution)

Power flow complexity at the distribution level and increasing need for electronic stabilization at both transmission and distribution levels are additional problems that come for the same set of new functions and grid changes. We can see that much of the problem stems from coupling of otherwise apparently siloed systems through the operation of markets and electrical physics of the grid.[20] This effect is immutable and is the source of many difficulties in grid management when new functions, particularly at distribution are deployed at scale without new control measures being put in place.

[17] De Martini, P., State of Distribution, Edison Electric Institute, July 2012, available online
[18] Medina, et al, Demand Response and Distribution Grid Operations: Opportunities and Challenges, IEEE Trans. On Smart Grid, September, 2010, pp 193-198
[19] Walling, et al, Summary of Distributed Resources Impact on Power Delivery Systems, IEEE Trans. On Power Delivery, July 2008, pp. 1636-1644
[20] De Martini, P., Chandy, K.M., Fromer, N. (editors), Grid 2020: Toward a Policy of Renewable and Distributed Energy Resources, Caltech Resnick Institute, 2012

## Modern Grid Architecture

The complexity of grid operation and control is increasing 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, developed by NIST[21], 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. Over the past several years much of the good work on interoperability standards led by NIST[22], as well as interface standards work via IEEE P2030[23] has focused on customer and customer device interfaces highlighted by the green boxes in the NIST diagram. The development effort related to IEC 61850 for substation automation and the IEC Common Information Model (CIM) have started to address the gap on controls oriented standards. But, the majority of interfaces represented by the lines among the yellow transmission and distribution boxes in the figure below are deficient in terms of interoperability and robustness to support the controls described in this paper. Physical interface standards such as IEEE 1547[24] also have shown limitations in functionality caused by the lack of a control framework. More is needed beyond these initial efforts and especially with regard to defining what info should be transferred via control protocols. The lack of an effective control framework also frustrates the implementation of the NIST cyber security guidelines and risk management methods developed by DoE.[25]

[21] NIST, NISTIR 7628 Guidelines for Smart Grid Cyber Security, 2010, available online
[22] Office of the National Coordinator for Smart Grid Interoperability, NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0, NIST Special Publications, January 2010. Available online
[23] IEEE 2030-2011 IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads, IEEE September 2011. Available online
[24] IEEE 1547 (2003) Standard for Interconnecting Distributed resources with Electric Power Systems, IEEE Standards Association, available online
[25] DOE-OE, Electricity Subsector Cybersecurity Risk Management Process, May 2012, available online

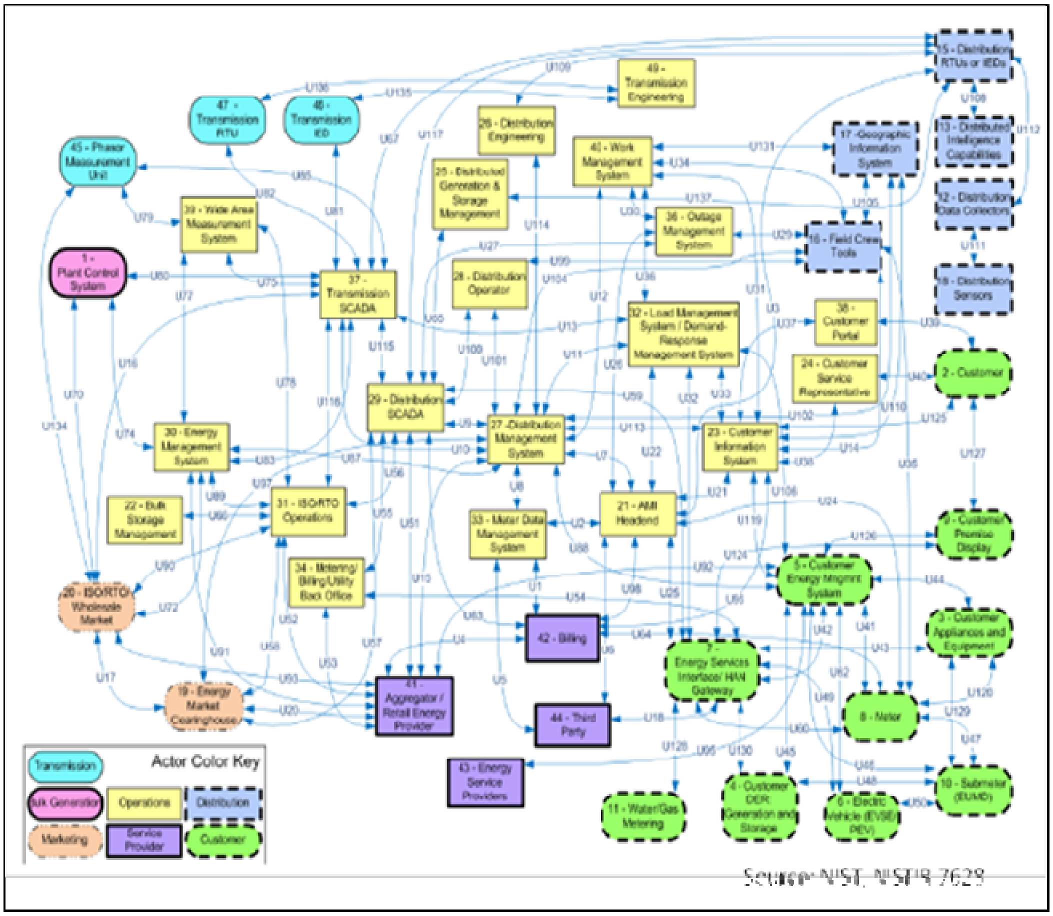


Figure 1. NIST/NISTR Grid Elements Diagram

If we consider the grid control problem (as opposed to protection, which due to its special nature deserves a level of discussion that is beyond the scope of this paper), then we are concerned with the following functions:

- Unit commitment, dispatch, and balance
- Power flow control
- Regulation of voltage, reactive power, and system frequency
- Stabilization and synchronization
- Variable and distributed energy resources integration, including distributed generation and storage
- Market integration as a control loop function, including price responsive loads
- Responsive load management, including demand response and EV charging
- Market participant behavior

Given this large set of functions, it is clear that the present control approaches involve multi-objective, multi-controller structures, and given the “hidden” interaction 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 – since a modern grid control system must support multiple objectives, it is 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 – the new control function involves 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 wide-ranging constraints into control solutions.

Robustness – many closed loop controls used in grid control are PI 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 $H_2/H_\infty$ control[26,27] adaptive critic network control[28] , etc. must be supportable.

Agility – since the grid of the future will undergo almost continual transition, as well as experiencing wide dynamic power state variations and various failures, the 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 system failures. Flow reconfiguration, stabilization and regulation across discontinuous failure events, and tolerance of unpredictable market behavior are all desirable. This has significant implications for the communication networks, network services, and network processes that support the control framework at all tiers.

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).[29,30] The SoS

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[26] Goncalves, et al, Multi-Objective Optimization Applied to Robust $H_2/H_\infty$ State Feedback Control Synthesis, Proceedings of the 2004 Control Conference, Boston, MA, June 30 – July 2, 2004

[27] Li, y., Rehtanz, C., et al, Wide Area Robust Coordination of HVDC and FACTS Controllers for Damping Multiple Interarea Oscillations, IEEE Trans. on Power Delivery, July 2012, pp. 1096-1105

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

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

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).[31] 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 prosumer endpoint, including markets, bulk generation with VER, transmission, distribution with DER, and responsive/transactive loads. We must also consider the multi-system 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. The long time scales involved in deployment 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. This gap is highlighted by research at Caltech, University of Florida and in a University of Illinois[32] paper last year,

> *"We strongly believe that a new paradigm for the design and operation of future energy markets is required. It is possible that in a few years all of the smart meters and wind farms installed today will be regarded as another "bridge to nowhere" unless we create the right architecture to make use of these resources, which must include reliable market mechanisms. In particular, we must move beyond traditional static competitive equilibrium analysis, and recognize the impact of dynamics and volatility. To this end, many of the issues surveyed here*

[30] Ncube, C. On the Engineering of Systems of Systems: Key Challenges for the Requirement Engineering Community, Software Systems Research Centre, available online.
[31] Peter Feiler, John Goodenough, et al, Ultra-Large-Scale Systems The Software Challenge of the Future, Software Engineering Institute, June 2006
[32] G. Wang, et al., Real-time Prices in an Entropic Grid, University of Illinois, Urbana-Champaign, 2011, available online

*require the application of successful power and energy methodologies of the past, complemented with approaches from other disciplines such as decision and control theory, simulation and learning. While, efficiency remains a key metric in design, we need to bring further objectives into the fold such as sustainability and reliability. Finally, the possibly adverse role of strategic interactions cannot be overstated and presents yet another challenge."*

For reference to the discussion in this paper, there is a difference between distributed control and decentralized control. The latter is much easier to implement and consists of moving some control functions in isolation to remote locations. True distributed control involves breaking a massive control problem down into a set of smaller problems, and solving the smaller problems on typically physically separated set of computing elements. Next, integrate all of the sub-problem results together to obtain the solution to the original large scale problem. This means that in the distributed case, the various elements are cooperating, not just performing locally. The difference can seem small on the surface, but the implications are large for developing the actual solution – hence the focus of this paper on layered decomposition methods as true distributed control methods. For example, a set of standalone apps pushed to cell phones is decentralized computing; a hierarchical set of optimization algorithms spread across the grid, working together to solve grid control, is distributed computing. At the physical level they can look the same; the difference is at the application level, which significantly shapes communication network requirements.

## Evolution of Grid Control Today

Newer grid functions of the types listed in the Emerging Trends section above are being gradually introduced to the grid with new controls alongside a wide variety of existing controls and control methods. The mix of control methods either in use or contemplated includes sophisticated optimization-based methods (unit commitment, economic dispatch, optimal power flow), simpler closed loop controls (PI control for Area Control Error), and open loop siloed controls (some load tap changers and capacitor controls for voltage regulation and voltage support, for example). This has resulted in the development of ad hoc approaches to link these various controls. Unfortunately, this chaotic situation is further compounded by the lack of true interoperability between and across many of these systems.

Figure 2 below depicts inter-tier control, with control flowing downward. It does not show the various kinds of control within a given tier, of which there can be many, although many of these control functions are listed in the tier blocks. Also, feedback paths, when they exist have been omitted from the diagram for clarity. 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 included in the control framework.

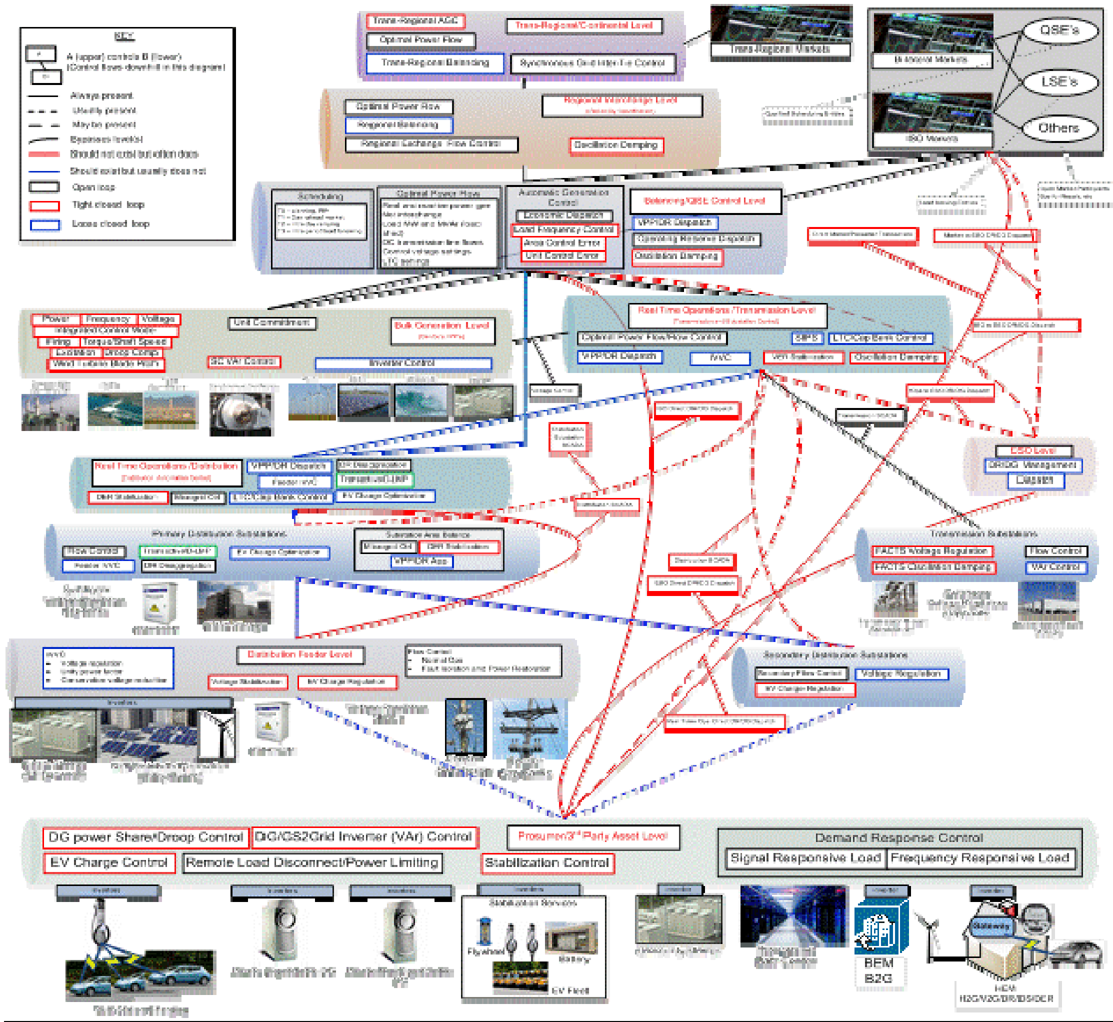


Figure 2. Grid Macro Control Reference Framework

The presence of markets as control elements bears a bit of examination, as policy clearly supports broader customer participation in markets through generation and demand based services. To-date, the approach has been to allow customer resources, connected at distribution, participate either directly or through non-utility aggregators. Current market and pricing policy for most DER generally applies wholesale models to distributed resources that do not reflect distribution level information related to location, reliability or power quality considerations. While this simplifies aspects of wholesale market operations, at scale this approach may create power quality issues at distribution and in the worst case reliability issues. This is because some market designs cause the market function to act as a control element in a feedback control loop, whether intended or not. This loop is closed around a substantial portion of the power delivery system, including multiple operational tiers as illustrated in Figure 3. Note that feedback of state variable (not system outputs) causes the equilibrium price to move so as to re-establish the balance between supply and demand, and moves in the equilibrium price cause changes in available generation, DR and DER.

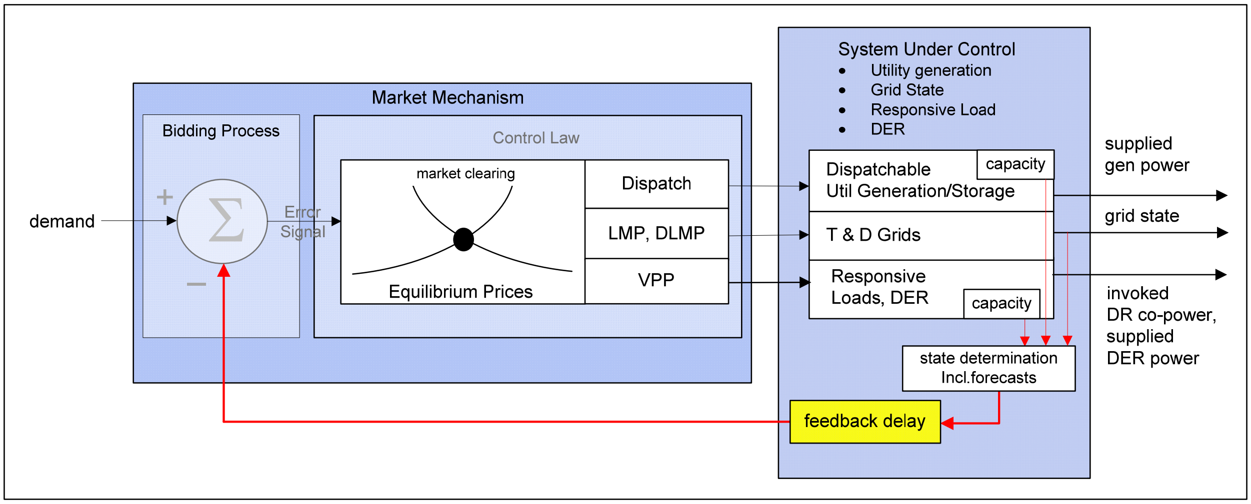


Figure 3. Power Markets as Feedback Controllers

Advocates of market prices to customers and devices will argue that is exactly the purpose – however, this point of view inevitably hasn't considered the effect of a wholesale based optimization on the lower tier distribution system. Traditionally, distribution was allowed to "float" based on tightly managing transmission system since power flowed in one direction. In a future with perhaps 30% of power being provided by solar PV at customer sites[33] these models break down quickly. It is becoming clearer that new distributed market mechanisms are needed.[34] The California Independent System Operator (CAISO) in a recent paper on DER pricing[35] acknowledged that distribution level factors need to be considered. However, the CAISO paper doesn't recognize the control loop issues and actually suggests a pricing model that is inconsistent with control architecture principles described earlier.

We argue that the curved red lines and ad hoc nested closed loops represent *emerging architectural chaos* in grid control. The problems here are several:

- 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

[33] McKinsey & Company, Solar power: Darkest before dawn, July 2012, available online
[34] G. Wang, et al. Dynamic Competitive Equilibria in Electricity Markets, University of Illinois, Urbana-Champaign, 2011, available online
[35] CAISO, Wholesale Grid State Indicator to Enable Price Responsive Demand, June 2012, available online

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.[36]

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

Each of these is useful in itself; the combination provides a strong framework for control systems for the grid of the future.

## Regularizing the Grid Control Macro Architecture

Step One is to regularize the macro structure of grid control by eliminating the emerging "chaos" with an inter-tier control flow arrangement that supports federation of both inter-tier and intra-tier controls, disaggregation for tier level grid control and provides a flexible framework for future innovation. Such a framework also has the benefit of integrating well with established principles of utility industry communication network design.[37] We can arrive at such a structure easily, by taking the reference framework of Figure 2 and first deleting the red lines, and then turning the blue lines to black. While sounding simple, this in fact implies changes in IT and communication infrastructure, as well as changes in business processes, none of which is simple to accomplish. If we do this architectural modification, we arrive at the structure of Figure 4, which is considerably simpler.

Keep in mind that the diagram represents inter-tier control flow, with flow going from top to bottom, and feedback paths are not shown. It includes Energy Service Organizations (ESO's), which are third party businesses that provide financial and/or technical services to the utility industry, in particular, such services as aggregation of Demand Response and Distributed generation, bidding these into power markets and in some cases actually dispatching the resources based on market clearing. This diagram does not imply, for example, that Energy Service Organizations do not have a function in the grid of the future; it just indicates how control flow with disaggregation, control federation, and constraint fusion must proceed. The structure is designed to align with grid structure and to respect both system and organizational boundaries. As we shall see, the existing grid control framework does not easily accommodate ESO's that would participate in grid operates in some fashion; the regularization of the grid control macro architecture would provide the framework to do this integration in a manner satisfactory to both the ESO's and the utilities.

Remember that control federation implies cross-boundary coordination but with local autonomy. This means that at any lower tier endpoints should be able to operate "selfishly", but within certain constraints set by the upper tier that maintain grid stability for example, or limit total power or observe any other useful and logical constraints. Disaggregation further supports local autonomy by enabling local tier controls to account for conditions and constraints in a manner suitable to that tier.

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[36] De Martini, P., Business & Policy Implications from DER, presentation at UCLA SMERC, March 2012
[37] Taft, J., Cisco GridBlocks Architecture: A Reference for Utility Network Design, Cisco, April 2012, available online

The diagram of Figure 4 does not illustrate the sub-structure inside of a tier. Such sub-structure certainly is needed at some tiers, but to illuminate this it will be helpful to consider the next step in the ULS control framework prescription process.

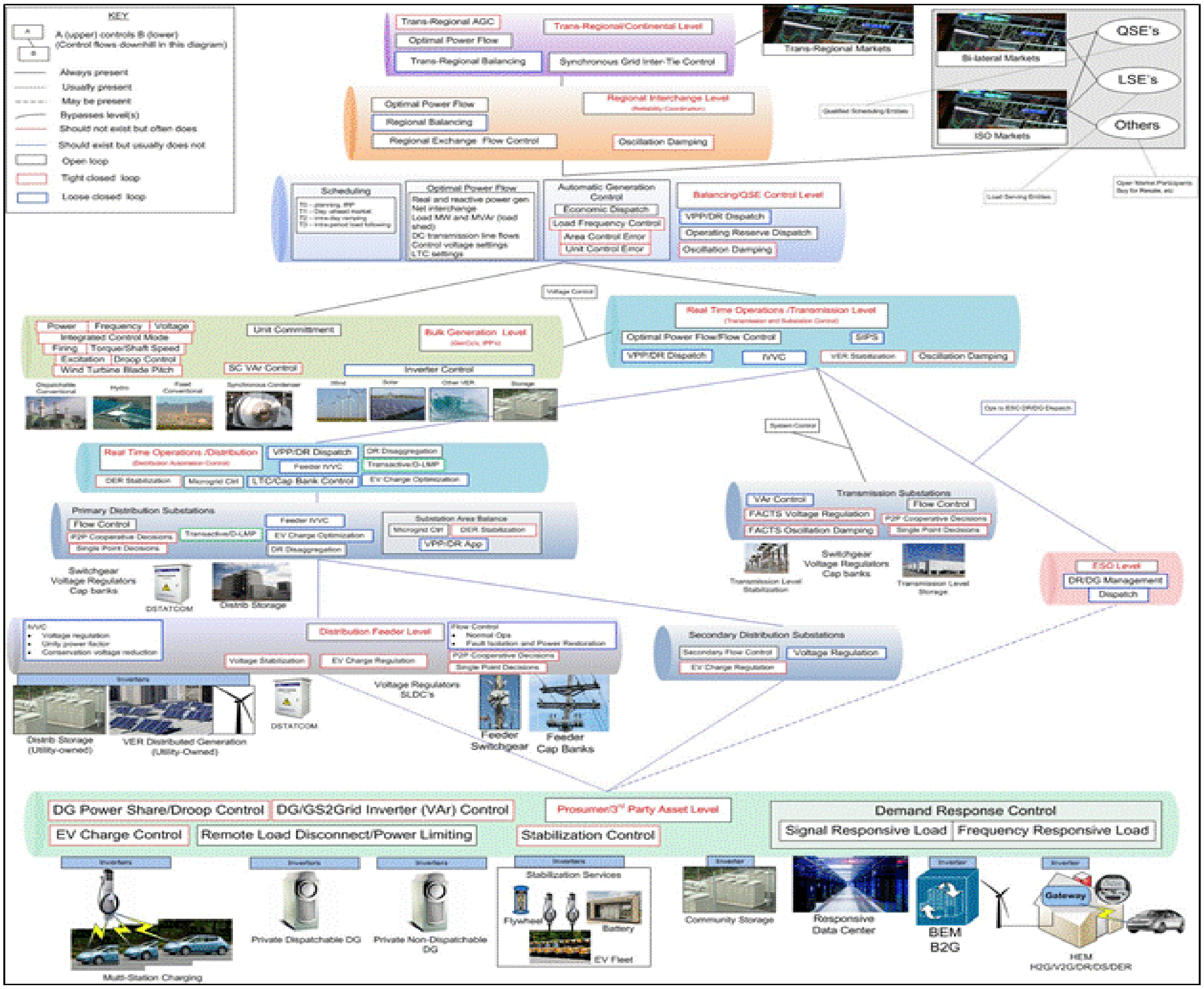


Figure 4. Regularized Grid Control Macro Structure

## Inter-Tier and Intra-Tier Distributed Control

Step Two involves structure to support distributed control along two axes:

- Vertical or inter-tier control – often called hierarchical control
- Horizontal or intra-tier control – bears a resemblance to parallel processing

Figure 5 below shows example of the vertical and horizontal axes. Note that there may be more than one horizontal distributed intelligence tier; the figure shows one at the primary distribution substation level, but others are possible and reasonable.

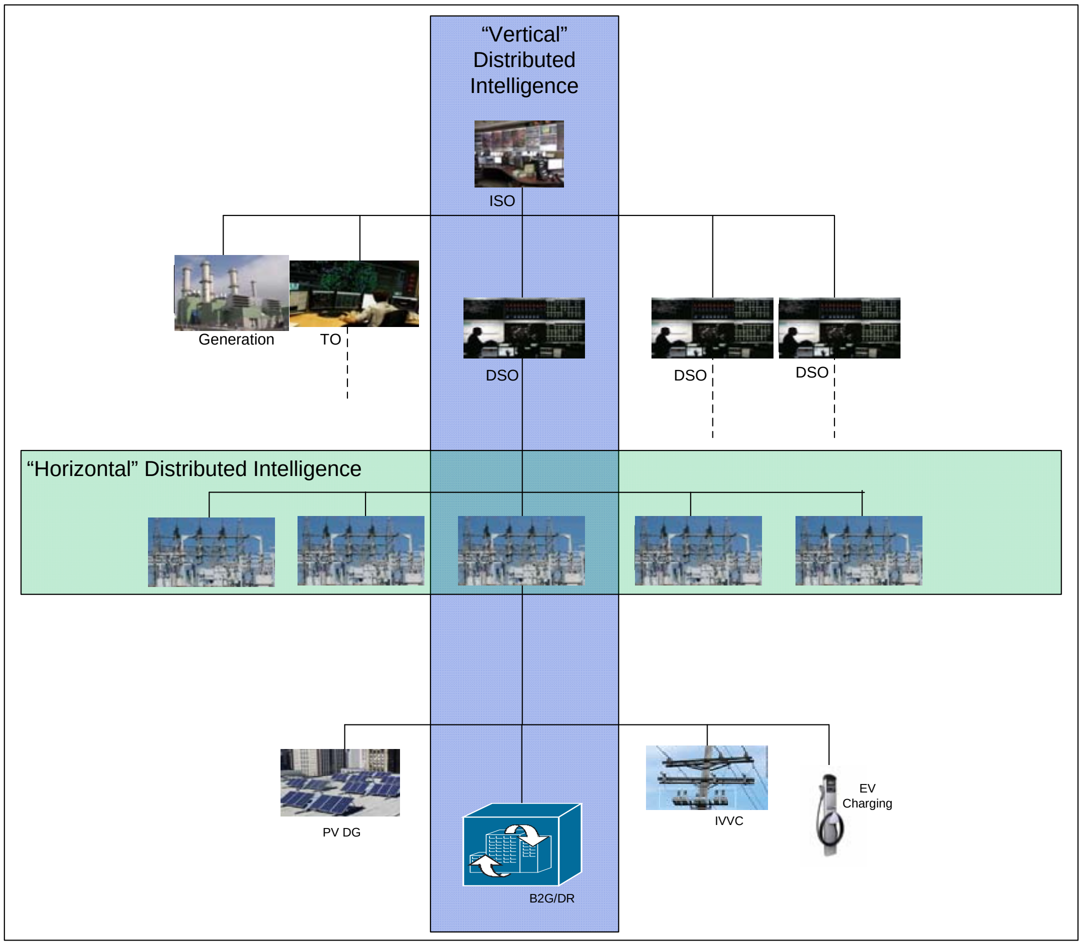


Figure 5. Vertical and Horizontal Distributed Intelligence

Regardless of the axis involved, distributed intelligence and distributed control offer compelling benefits, which include:

- ☐ Problem Complexity Decomposition
  - Distribution in either axis allows complex problems to be broken into smaller parts which are easier to solve and can be solved using multiple processors, thus providing built-in scalability
  - Distributed implementations also facilitate modular incremental rollouts that grow appropriately and automatically as the system grows  or control deployment proceeds
- ☐ Temporal Alignment
  - Distributed intelligence architecture can align the operational timing needs of specific control applications with related data sources and processing. Such as, the ability to enable low latency response to an event through the ability to process data and  provide it to the end device without a round trip back to a control center

- Low Sampling Time Skew can be achieved through multiple data collection agents and can easily minimize first-to-last sample time skew for improved system state snapshots compared to round robin sampling

- Scalability
  - No single choke point for data acquisition or processing; analytics at the lower levels of a hierarchical distributed system can be processed and passed on to higher levels in the hierarchy. Such an arrangement can keep the data volumes at each level roughly constant by transforming large volumes of low level data into smaller volumes of data containing the relevant information. This also helps with managing the bursty asynchronous event message data that smart grids can generate (example: last gasp messages from meters during a momentary fault)
- Robustness
  - Local autonomous operation is easily supported
  - Continued operation in the presence of communication network fragmentation is possible
  - Graceful system performance and functional degradation in the face of device and subsystem failures is achievable
  - Incremental rollout can easily be accomplished if the underlying software supports dynamic topology and zero touch deployment

Distributed processing also brings issues of its own, such as:

- Device/system/application management – smart devices residing in substations, on poles, in underground structures represent significant cost to visit. It is impractical to send a person out to all of these devices to install a patch, reset a processor, or upgrade an application. Remote administration of smart devices on a power grid is necessary. This also implies remote monitoring of not just the devices themselves, but the databases and applications, along with the means to reset, patch, and upgrade remotely.

- Harder to design, commission, and diagnose – distributed intelligence systems can inherently involve a larger number of interfaces and interactions than centralized systems, making design, test, and installation more complex than with centralized systems.

- More complex communications architectures required – distributed intelligence involves more peer-to-peer interaction than with centralized systems, so that the communication network must support the associated peer-to-peer communications. The resultant networks are more complicated than a standard radial hierarchical topology.

Techniques developed for the communication networking industry can provide means to address these issues. Such methods include the aforementioned zero touch deployment model and use of the standards based IP protocol suite. The value of the IP protocol suite and of advanced networking is that it provides more than just data pipes for distributed systems; it provides a platform upon which distributed applications can run. This is due to the nature of the advanced protocols that support system operation with capabilities such as network-enabled data publish-and-subscribe mechanisms (Source Specific

Multicast for example), the integration of networking with virtualized computational elements, communication network management tools, and integrated data security are all made possible due to the power of the IP protocol suite. In addition, the layered approach to communication network security exemplified by the IP protocol model insulates each layer from changes in the others, thus making IP a key to future-proofing investments in communication technologies that will change as grid control requirements change.

Inter-tier (Hierarchical) Structure

The "vertical" distributed control axis is properly known in control engineering as hierarchical control. Figure 6 illustrates a simple view of hierarchical control. Note that there may be multiple local controllers and these controllers may have peer-type interactions. They are supervised by a higher level regional controller, which may provide set points to the local controllers, or may actually close loops around the larger regional domain. We may observe such a structure in the way that Area Control Error (ACE) is employed in area balancing.[38]

The diagram of Figure 4 hints at something we will examine in greater detail later in this paper. Specifically, that within a tier, there must be additional control structure to support not only individual local controllers, but also local controller interaction. We mentioned earlier the issue of control federation – this arises on the local level when multiple controllers either want to impact the same infrastructure or grid variables, or when coupling through the electrical physics of the grid makes it necessary for local controllers to interact to avoid the undesired consequences of such "hidden layer" interaction. This is part of the "horizontal" distributed control axis.

First, we focus on the vertical axis interactions. It is possible to move responsibility for local interactions to the regional controller level, but in low latency control loop situations this may prove difficult to design and implement with acceptable control loop performance. More often, the regional coordinator has the role of supervisory controller, providing set points and handling exceptions that exceed the capability of a local controller to handle. In some designs, the regional controller sets trajectories for the local controllers to follow, based on the solution to an optimization problem.

The simple hierarchical control of Figure 6 has long since been expanded to multi-level control, with as many tiers as are needed for any given control problem.[39] This control approach provides for decomposition of large complex control problems down into a series of smaller sub-problems, with the sub-problems being integrated via the hierarchy to solve the entire original control problem. The hierarchical control model has been in wide use in the electric utility industry in specific way for many decades. The aforementioned ACE method is one example; SCADA for distribution grids is another. We contend that this model should be employed systematically in line with the regularized framework of Figure 4 above and with items to be introduced in the next section.

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[38] NERC Resources Subcommittee, Balancing and Frequency Control (Part 1), NERC, November, 2009. Available online

[39] Chee-Yee Chong and Michael Athans, On the Periodic Coordination of Linear Stochastic Systems, Proceedings of 1975 International Federation of Automatic Control, August 1975

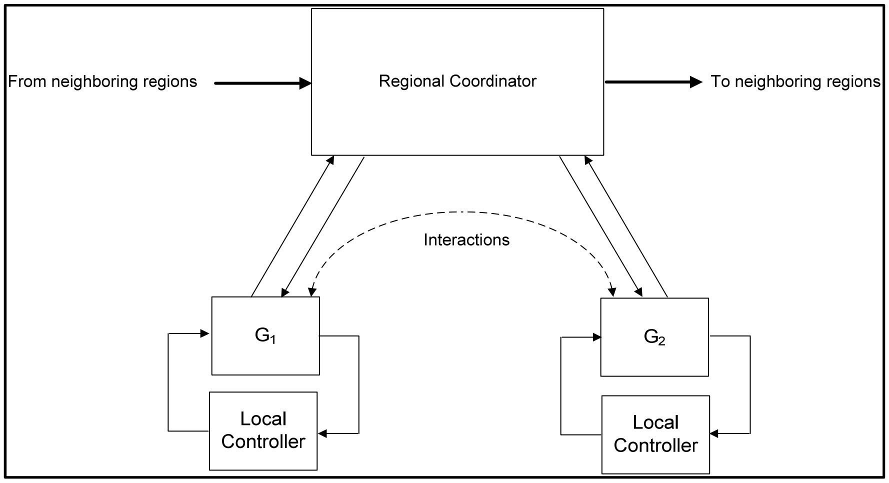


Figure 6. Simple Hierarchical Control

The simplest decomposition to envision is one that distributed control from control centers to primary substations, and from there to distribution level devices, and finally to non-utility assets, such as responsive loads. This decomposition is straightforward but in practice is too limiting, in that it forces every substation to be a supervisory control point. In practice, we have seen designs that allocate supervisory control functions for several substations to a single substation, and designs that allow for such supervisory control functions to be dynamically allocated and re-allocated. Given the available technologies, we can be more flexible in terms of hierarchical structure mapping to physical grid infrastructure. Figure 7 illustrates a more flexible approach to mapping hierarchical control onto grid infrastructure. Here we define a set of hierarchical regional domains which we somewhat arbitrarily designated *control area, system, zone, local area, and sector*.

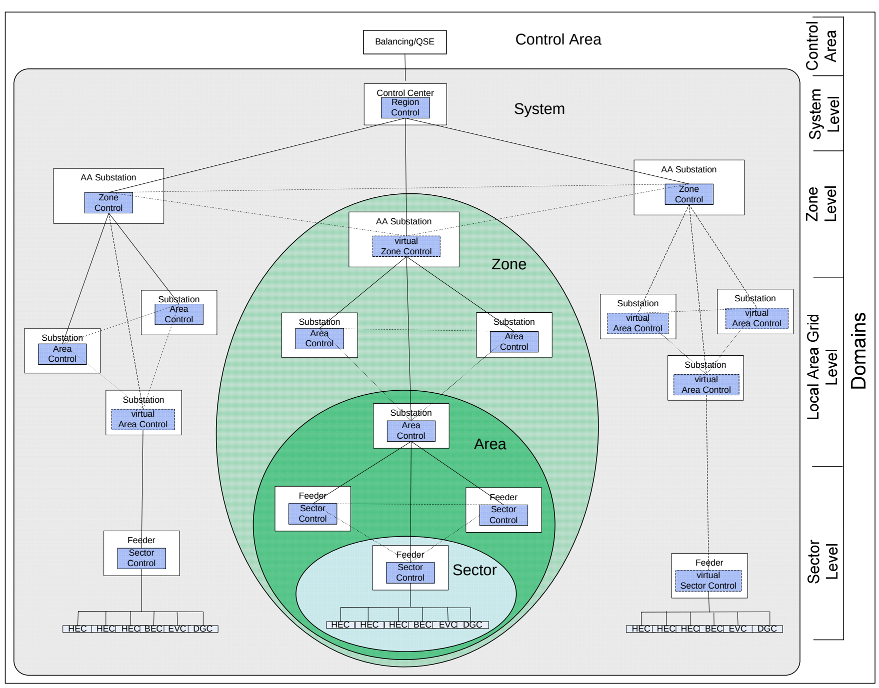


Figure 7. Illustration of Hierarchical Domains

Note that supervisory control is designated with either a solid or a heavy dashed line. A solid line indicates that the upper box supervises the lower and that local control resides in the lower box. A heavy dashed line indicates that local control acting as if it resides in the lower box actually resides in the upper box and so is virtualized. Dotted lines indicate peer interaction. Using this virtualization model, we may flexibly assign control functions to various points in the infrastructure, allowing AA substations to handle all of the control functions for several standard substations for example, and we may dynamically move control functions from one location to another to suit varying grid conditions. The net of this is that logical hierarchical control structure and physical infrastructure do not have to match in order for the control hierarchy to exist, but certainly the mapping will employ distributed physical assets of the utilities.

<u>Intra-Tier Sub-structure</u>

The architectural we propose framework recognizes the need for sub-structure within each tier. A three sub-tier structure, such as depicted in Figure 8, provides the necessary foundation. It is not necessary for all three sub-tiers to exist at every major tier of Figure 4, but the framework for such sub-structure should be present in the architecture.

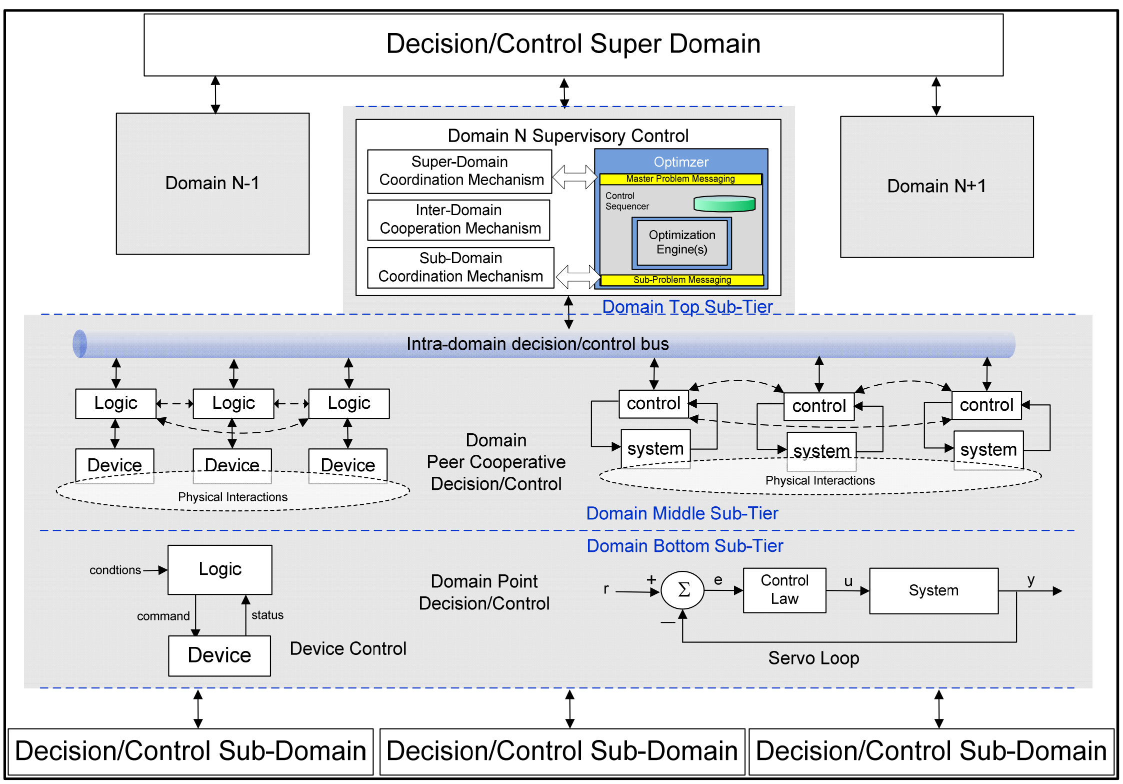


Figure 8. Intra-Tier Sub-Structure

The three sub-tiers are:

- Domain Point decision/control – local control loops and decision mechanisms that operate independently but may use set points and other inputs from a higher level supervisory control – this is traditional "horizontal" distributed control

- Domain peer cooperative decision/control – the mid-level sub-tier in which local controls and decision processes interact with peers at the same level to cooperate on grid management
- Domain supervisory decision/control – optional top sub-tier that provides for domain level supervisory decision and control plus three other functions:
  - Inter-domain peer cooperation mechanism
  - Interface to hierarchical supervisory control from above
  - Optional domain level optimization engine

The purpose of the optimization engine option is explained in the next section, which describes the third step in the macro control framework rationalization process.

## Optimization in Grid Control Design and Implementation

Step Three in the process is to introduce distributed optimization in a systematic way across the full control architecture. There are several reasons for this but they have less to do with finding optimal solutions than with being able to handle complexity. Emerging grid control problems are characterized by high complexity, multiple constraints and objectives, cross organizational boundary and cross tier functions and impacts, and the desirability of distributed implementations.

There is a long standing relationship between distributed control and optimization. Many distributed control problems have solutions based on optimization theory dating back to the 1970's.[40,41] More recently, there has been a focus on using optimization methods to solve grid control problems, not because the optimal solution is that much better than the "good" solution, but because the new problems involve large numbers of constraints and optimization methods provide tools to handle such situations. We have also seen the emergence of new optimization methods, and in particular the primal-dual decomposition approaches inspired by Network Utility Maximization (NUM), which was originally developed for congestion control in communication networks, but which has application to multi-layer optimization.[42,43]

The primal-dual decomposition technique and its variants provide a useful way to apply optimization to hierarchical control. By decomposing a large scale grid control problem into layers, and by mapping those layers to the region decomposition and further to the available infrastructure outlined in the discussion above on Inter-Tier (Hierarchical) Structure. Starting with the Network Utility Maximization formulation, optimization problems may be decomposed into layers using the primal approach in which the master problem controls the sub-problems by allocating resources; alternately in dual decomposition, the master problem may control the sub-problems by using pricing. Either way, control problems may be decomposed into layers that match hierarchical grid control layers as well as intra-tier control elements.

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[40] T. B. Cline and R. E. Larson, Decision and Control in Large Scale Systems via Spatial Dynamic Programming, Lawrence Symposium on Systems and Decision Sciences, Berkeley, CA, October 1977
[41] Robert E. Larson, A Survey of Distributed Control Techniques, Tutorial: Distributed Control, Chapter 5, pp. 217-261, IEEE Catalog No. EHO 153-7, 1979
[42] Mung Chiang, Steven Low, et al, Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures
[43] Daniel P. Palomar and Mung Chiang, A Tutorial on Decomposition Methods for Network Utility Maximization, IEEE Journal on Selected Areas in Communication, August 2006, pp. 1439-1451

By applying system level control criteria and constraints at the upper levels, and then allowing the lower levels to optimize "selfishly" within the bounds set by the upper layers, we can arrive at a macro control framework that encompasses both traditional and emerging control functions and models and allows for incremental transition from fully centralized to variable topology distributed control structures while maintaining overall grid stability and constraint compliance. Figure 9 shows the two main methods for performing the layer decomposition, and illustrates performing multiple decompositions to obtain a three layer decomposition. Note that we can use primal and dual decompositions in any order and any mix. For example, we could use a primal decomposition followed by a dual decomposition, or use two dual decompositions, etc.

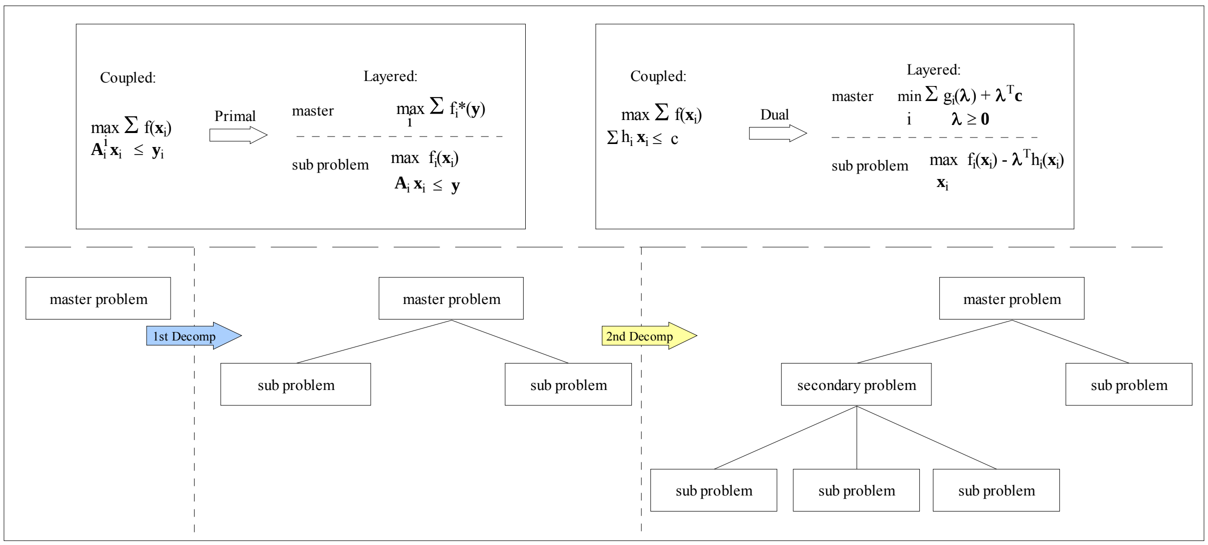


Figure 9. Layered Decomposition for Distributed Grid Control

The approach can be applied to as many tiers as is required, so that tiers can be defined as necessary. Individual control points may be in control centers and substations, or may embedded in devices such as controllers for FACTS and distribution-level power electronics devices, capacitors, load tap changers, intelligent EV chargers, or even household appliances. Figure 10 shows an example of mapping the layered optimization decomposition onto a power delivery infrastructure.

On the left of Figure 10, a power delivery system is depicted, from ISO down through to customer endpoints. On the right, the distributed optimal control elements are mapped to the same exact structure, with the distributed control elements being located at points in the power system such as control centers, substations, and in the case of advanced responsive customer assets, in those assets themselves.

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.[44]

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 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. 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. This 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.

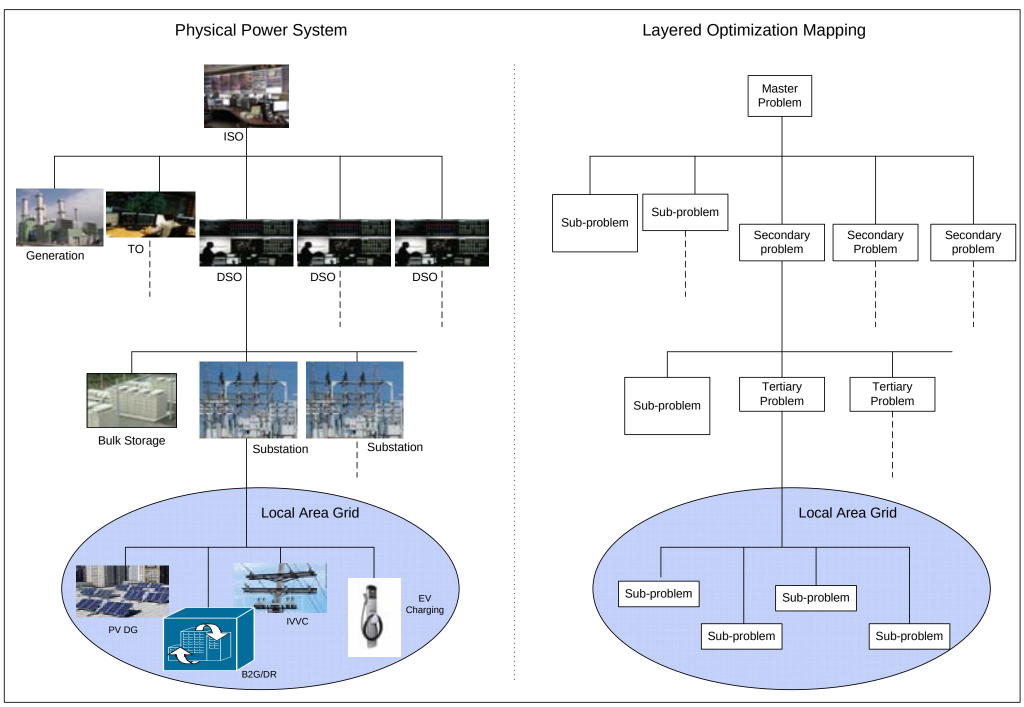


Figure 10. Example Mapping of Optimization Layers onto Power System Infrastructure

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[44] Daniel P. Palomar and Mung Chiang, Alternative Distributed Algorithms for Network Utility Maximization: Framework and Applications, IEEE Trans. On Automatic Control, December 2007, pp. 2254-2269

In summary, the layered optimization decomposition approach, when combined with the concept of vertical and horizontal distributed intelligence and control and framework regularization yields:

- A clean control framework for the entire power delivery system that eliminates architectural chaos
- A means to incorporate complicated new functions and constraints while maintaining system stability and security
- A means to coordinate control at multiple levels while enabling each level to operate in a manner based on local tier level requirements and constraints
- A method to allow any tier level control to provide coordination signals to devices, systems, and organizations at lower tiers and to accepts such coordination from tiers above
- A framework to provide the context for interoperability standards
- The structure for any tier to use optimization along with local decision and control and peer to peer interaction to provide flexible control capabilities that accommodate generally accepted grid controls but also enable advanced capabilities as they are needed
- A framework that provides the means to integrate third party (non-utility) interaction with grid control in an operationally non-disruptive manner.

The implementation of this framework can be started incrementally at any level or at multiple levels simultaneously. A key to multi-level operation will be the layer boundary interfaces. Careful specification of layer boundary interfaces will unify a number of emerging control philosophies, such as transactive control, distribution locational marginal pricing, and local area grid operations.

## 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. A comprehensive ultra-large scale control framework offers an effective reference to develop modern grid control-based architectures and related interoperability standards and product designs.

Specifically, the issue can be resolved by in three steps: first, remove some of the emerging lines of control that are not sustainable at scale and regularize the lines of inter-tier control; second, introduce a comprehensive distributed control framework that has both horizontal and vertical axes; third, apply modern optimization methods such as layered primal-dual decomposition to solve the large scale control problems in a fashion that allows for multiple competing objectives, multiple constraints, and provides for both control federation and disaggregation so that each utility and energy service organization has the ability to solve its local grid management problems, but within an overall framework that ensure grid stability.

The most immediate attention should be paid to the areas where architectural chaos is emerging fastest and where investment decisions are most imminent. This would include:

- Distribution system operations and local area grid management
- Market connections to customers/prosumers and integration of local markets
- Disaggregation of ISO-level outputs through DSO's to responsive loads

The modular, layered nature of the control framework describes in this paper makes it possible to attack these problems in manageable stages.

This situation is avoidable. However, if not addressed quickly the electric industry may face an increasingly unmanageable patchwork of grid control implementations that is not sustainable at large scale. Grid owners and operators face a significant increase in operating expenses related to running these complex ad hoc systems. The current ad hoc system complexity in certain circumstances may create unstable conditions and significant grid reliability risks. The current approach makes it very difficult, if not impossible to implement effective security schemes at scale. Worse yet, failure to address these control system issues as proposed in this paper may result in the potential for substantial expense and premature asset write-off to replace stranded investments in first generation smart grid technology.