Ultra-Large Scale Control Architecture

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Abstract—**Electric power grid complexity is growing rapidly as we attempt to support technical, business, and societal goals for which power grids were not originally designed. To ensure grid stability and have the ability to remain reliable under highly dynamic destabilizing conditions requires that grid control systems evolve in ways that address transformational changes and the resultant operational problems. Ultra-large scale power system control architecture - a macro architecture for grid control that handles multi-objective, multi-constraint problems in a framework that can support coordinated control across utility organizational boundaries and, potentially, prosumer premises. 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.**

Keywords—controls; architecture; distributed resources; markets

I. Introduction

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.

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. This architectural exigency is resulting in an emerging chaos in grid control system macro-architecture that is unsustainable and inherently unsecure on several dimensions.

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 along with a three step framework to address the emerging complexity. 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.

II. Grid Control Evolution

Today, 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. To architect a modern grid at scale, it is necessary to go beyond concepts such as System of Systems [1] and make use of the concept of Ultra-Large Scale Systems (ULS) [2].

The ULS paradigm allows consideration of the macro-scale control architecture of the entire power delivery chain, from balancing to prosumer endpoint, including markets, bulk generation, transmission, distribution with Distributed Energy Resources (DER). It is also necessary to 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. Finally, utilization of design and implementation methods powerful enough to solve the control problem in this complex environment is required. 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. 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;

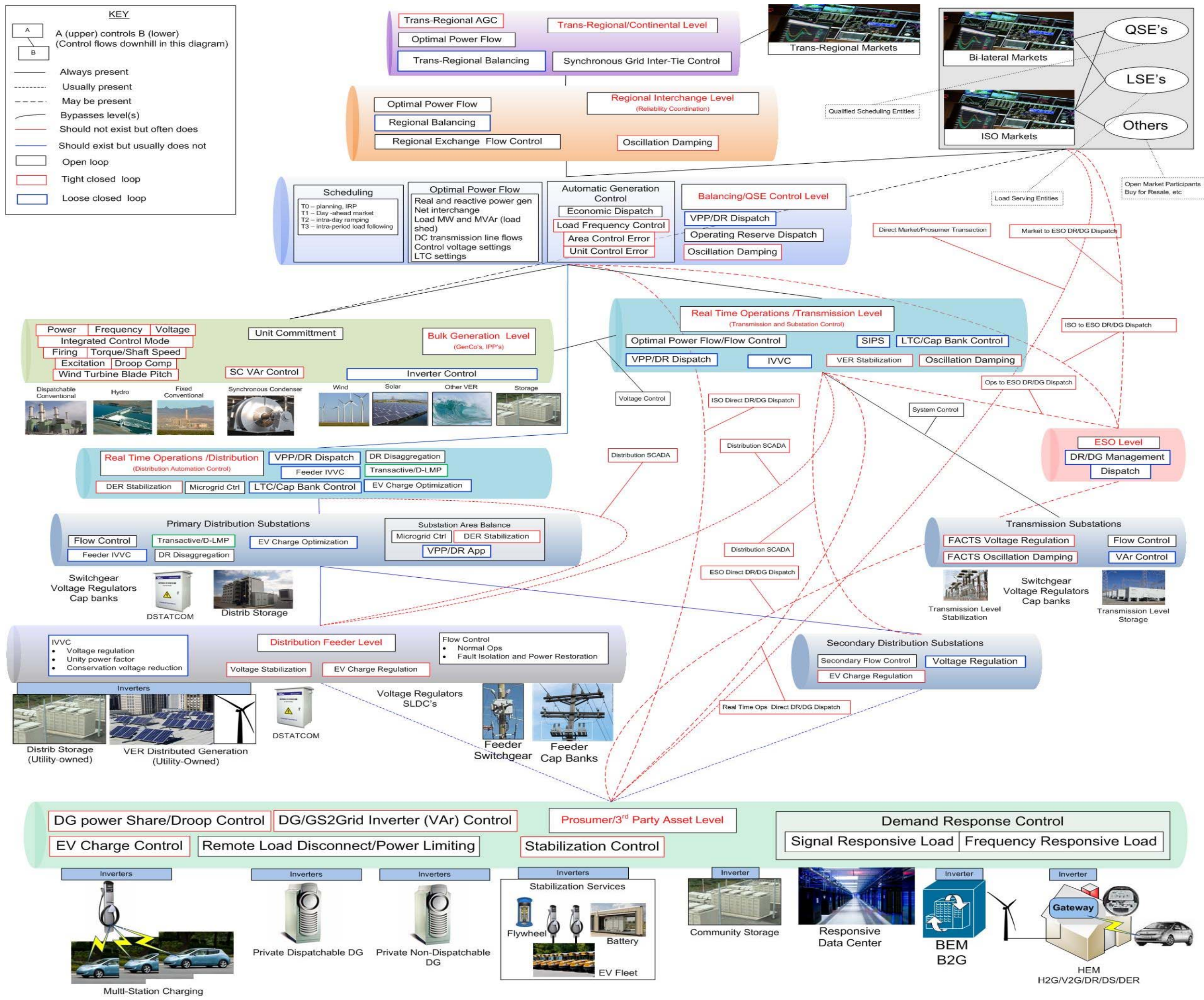

Figure 1 Existing and Emerging Inter-tier Grid Controls

others are solved using traditional control engineering or ad hoc methods.

Figure 1 above depicts existing and emerging inter-tier control, with control flowing downward in today's systems. 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 a few key observations can be made:

- Traditional control (straight 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.
- Curved lines on the right represent mostly newer ad hoc controls, although in at least one case (distribution SCADA) the curved line has been used as a matter of practical necessity. Most of the curved 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.

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,

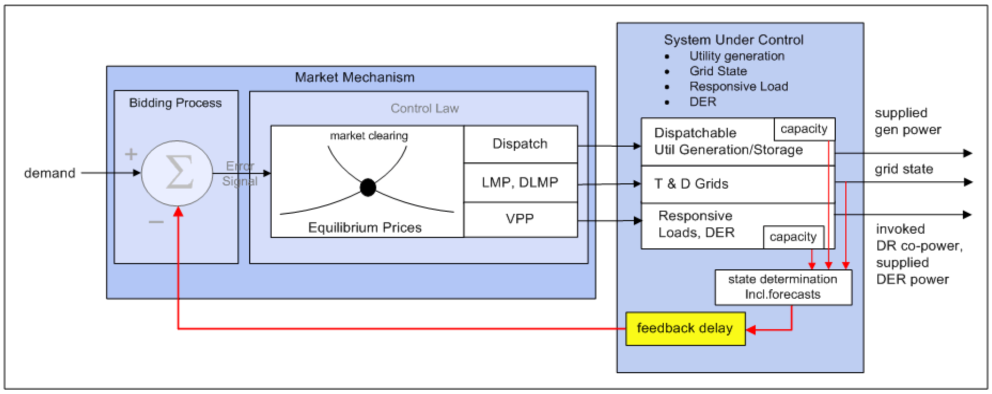

Figure 2 Power Markets as Feedback Controllers

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 2. Note that feedback of state variables (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 and DER.

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% or more of power flows on distribution networks from distributed generation these models break down quickly. 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
- This 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. 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. Optimizing grid design and implementation

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

III. Regularizing 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 [3]. Such a structure is easily derived by taking the reference framework of Figure 1 and first deleting the curved lines, and returning to a clean layered framework. While this sounds simple when put that way, in fact this implies changes in IT and communication infrastructure, as well as changes in business processes, none of which is simple to accomplish. This architectural restructuring produces the regularized structure of Figure 3 below, which is considerably simpler in structure.

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

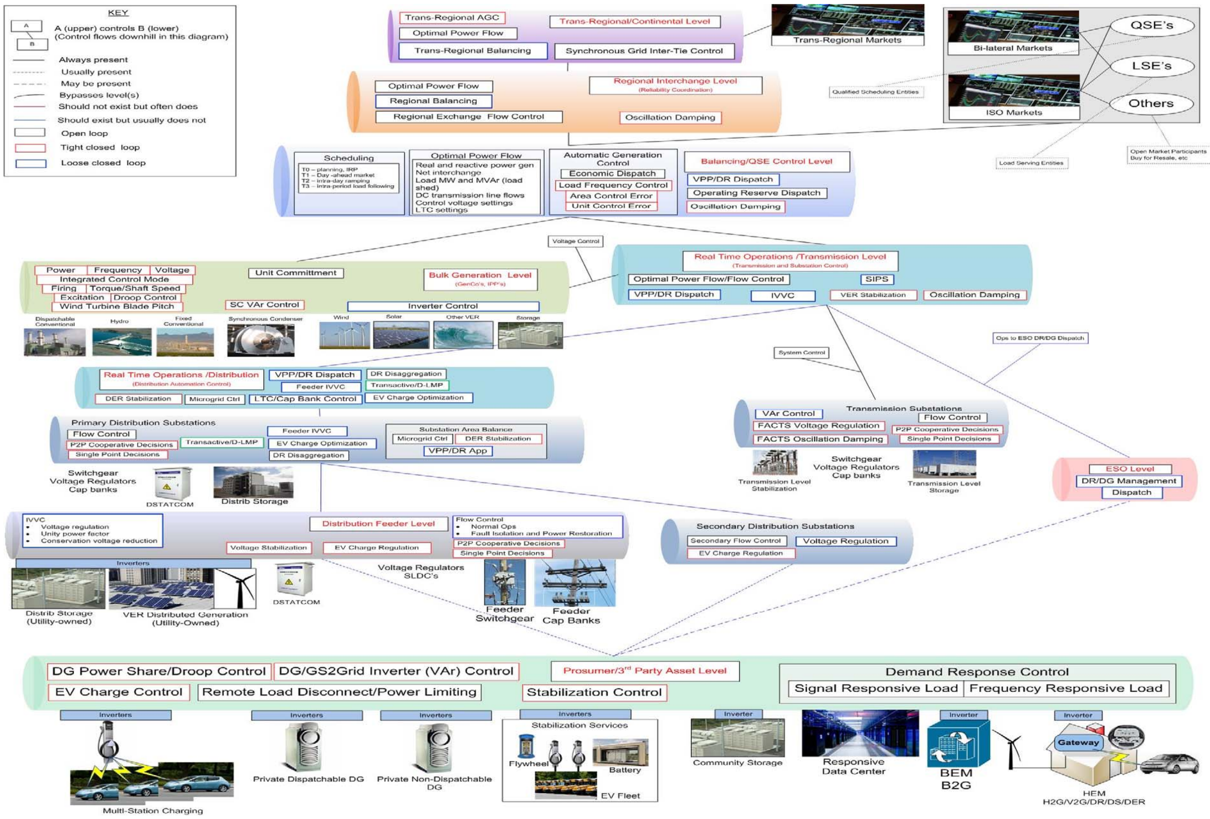

Figure 3 Regularized Grid Control Macro Structure

and to respect both system and organizational boundaries. 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.

The diagram of Figure 3 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.

IV. Vertical and Horizontal Distributed Control

Step Two involves structure to support distributed control along two axes: vertical or inter-tier control (often called hierarchical control), and horizontal or intra-tier control (which bears a resemblance to parallel processing).

Figure 4 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.

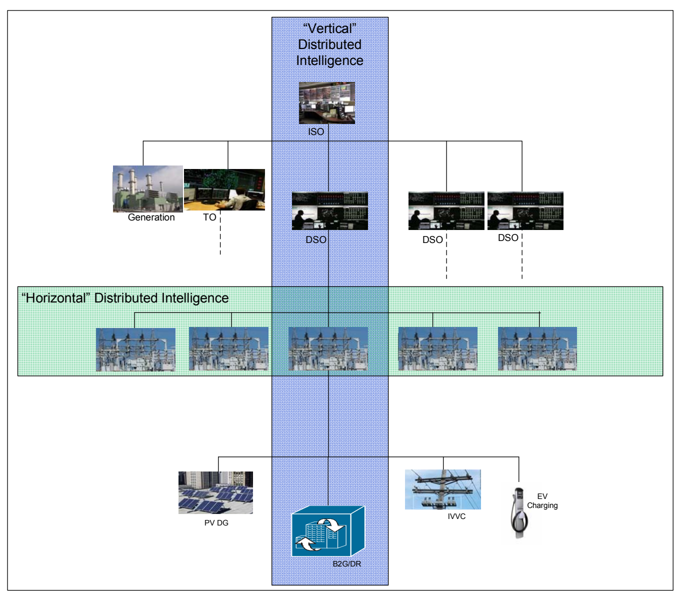

Figure 4 Vertical and Horizontal Distributed Intelligence

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 thus providing built-in scalability. This approach also enables problems to be solved using multiple processors. As such, distributed implementations also facilitate incremental system deployments that grow appropriately and automatically as the systems grow or control deployment proceeds. This is an important consideration in addressing the new control system requirements for integration of distributed generation on a distribution system.

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 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. Device/system/application management of smart devices residing in substations, on poles, in underground structures represents significant cost to visit. Even more so than that with a PC network, it is impractical to send a person out to any 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. Distributed intelligence systems are harder to design, commission, and diagnose as they inherently involve a larger number of interfaces and interactions than centralized systems, making design, test, and installation more complex than with centralized systems. Also, more complex communications architectures required as 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 for a simple star.

However, techniques developed for the communication networking industry can provide means to address these issues. Such methods include the aforementioned zero touch deployment and use of the IP protocol suite (not the internet itself but the set of networking protocols collectively known as the Internet 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. 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.

V. 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 [5]. 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. The emergence of new optimization methods, and in particular the primal-dual decomposition approaches inspired by Network Utility Maximization (NUM) [6],[7] originally developed for congestion control in communication networks, but which also have application to multi-layer optimization.

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. 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, it is possible to 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 5 shows the two main methods for performing the layer decomposition, and illustrates performing multiple decompositions to obtain three-layer decomposition. Note that it is possible to use primal and dual decompositions in any order and any mix. For example, use of a primal decomposition followed by a dual decomposition, or use of two dual decompositions, as needed.

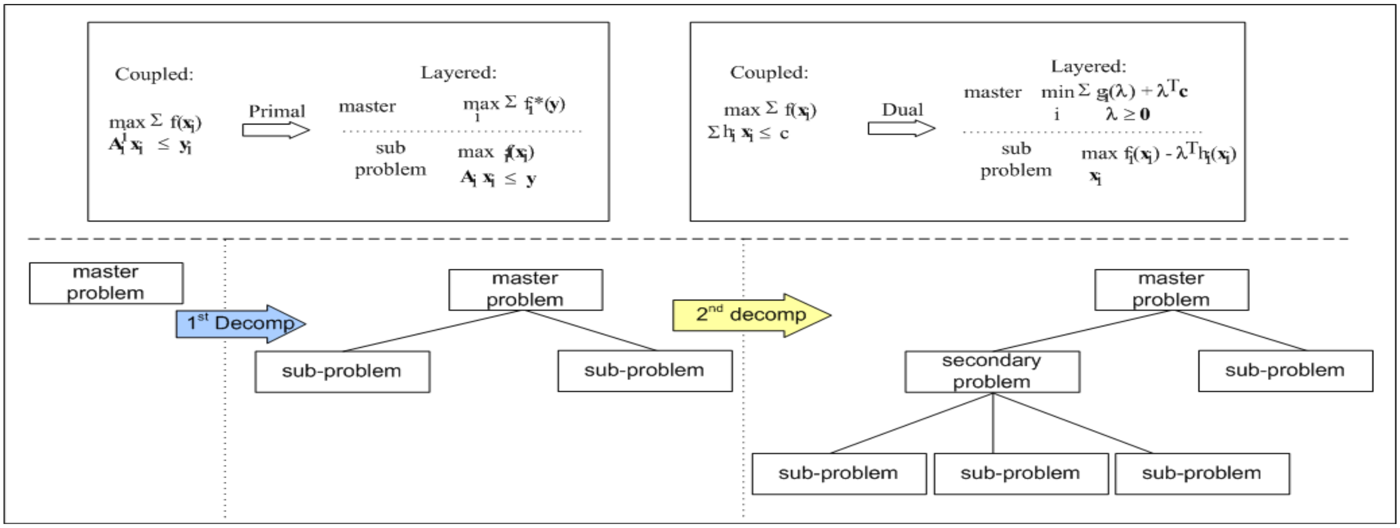

Figure 1 Layered Decomposition for Distributed Grid Control

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.

VI. SUMMARY

This modern grid control architectural framework provides the means to properly integrate new functionality in a rational way and enables both centralized and distributed implementations. 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.

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.

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