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Ultra Large-Scale Power System Control Architecture

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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 behaviour 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 - 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

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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 ultra-large scale architecture for grid control that can solve today's problems and those expected over the next 30 years.

KEYWORDS

Power Grid, Architecture, Optimization, Distributed Control, Distributed Intelligence, System

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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 Trends Affecting Grid Control System Design

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. 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 and the second is that they may cause “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. These include unfortunate interactions of Volt/VAr control and demand response, control mis-operation, 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:

- Variable Energy Resources integration (transmission level)
- Wide area measurement, protection, and closed loop control
- Distributed Energy Resources 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 network and microgrid power balance and flow control
- Multi-tier virtual power plants

- Energy/power market interactions for prosumers and Transactive Energy
- 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. 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.

Principles for a Modern Grid Architecture

In this paper we shall discuss control system architecture, which is a topic that is not often considered separately from control engineering design and rarely is applied to the entire multi-organization/multi-system power delivery chain. Figure 1 illustrates an abstraction model for grid control. In this discussion we shall concentrate on the top two layers, where the bulk of the control architecture decisions are made.

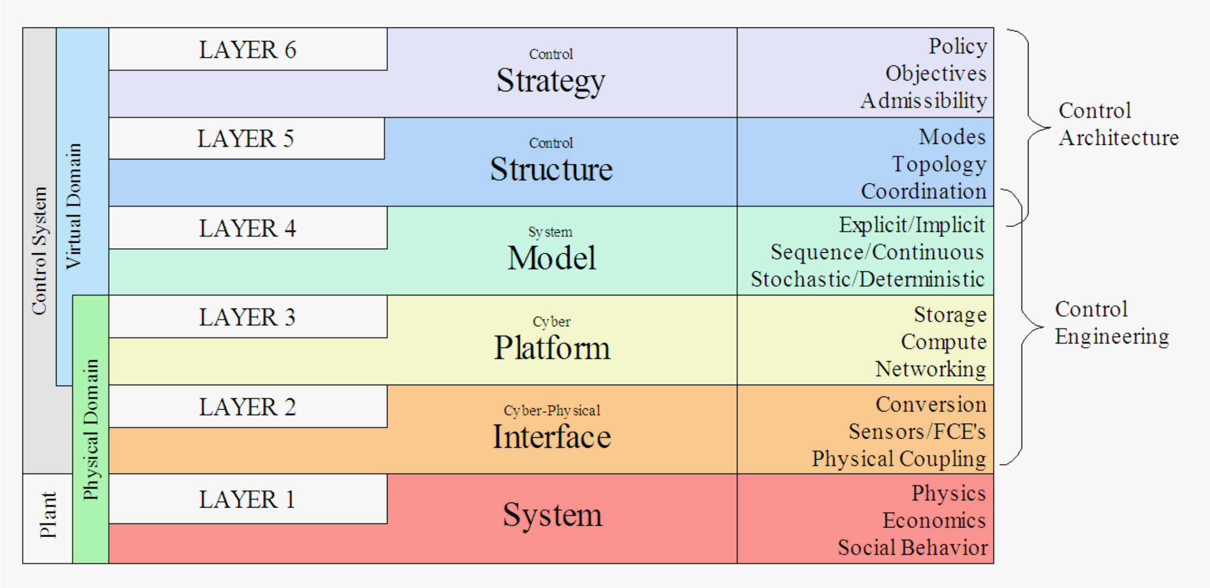

Figure 1. Control Abstraction Model

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.

Coordination – Hierarchical and distributed control require a process or capability known in control engineering as *coordination*. Multiple coordination methods have been developed, going back as far as the 1960's, but they have not been strongly applied in grid control because they have not been needed until now. The emergence of new grid requirements and structures, especially at the distribution level, has brought the need for *deep-area coordination* to prominence.

Boundary Deference – While not often discussed in control engineering, this issue is of prime importance in any modern power delivery system, and doubly so in disaggregated environments. Any control framework that spans multiple organizations or multiple systems or both must have a mechanism for respecting those boundaries. This means that local control must be able to use local performance criteria and must be able to observe local constraints, even when operating in a coordinated framework. We see this today to some extent in functions like control area balancing, but future power grids must have an effective means to do this in a more general way for all aspects of grid control.

Resilience – 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 behaviour are all necessary.

Ultra-Large Scale Control Architecture

The architectural reference model for future grids must be reconsidered. Over the past 10 years, 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 such as are 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 (physical, ICT, financial, social), 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/DR endpoint. 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. Long deployment time scales mean that architectures must support variable topologies and placement of functions while a utility does a build-out of new capabilities or cyber infrastructure. ULS anticipates these issues whereas SoS (especially as implemented via Service Oriented Architecture or SOA methods) treats them only incidentally..

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 methods and structures are becoming inadequate for the power grid of the future. Addressing these issues involves three major elements:

1. Providing an ultra-large scale coordination framework for grid control
2. Applying newer methods to design of control systems for the grid
3. Implementing distributed measurement and control with centralized application management

Multi-Layer Optimization Decomposition for Deep Area Coordination

The layered decomposition can be applied recursively to accommodate not only grid structure hierarchy, but also system and organizational boundaries (see Figure 2 below).By using the layering for optimization decomposition technique [8] along with a 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.

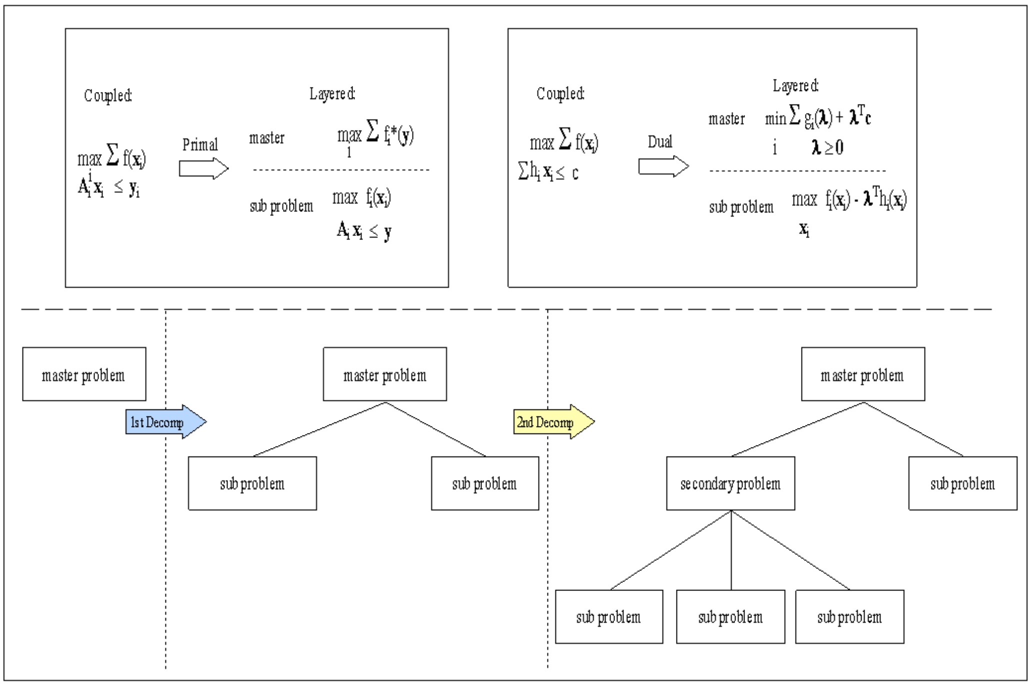

Figure 2. Layering for Optimization Decomposition

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.

This approach provides a very flexible basis for formulation of advanced grid control problems in an optimization framework. The use of optimization methods in grid control design has obtained much currency in the last two years, but not for the reason of achieving optimality. The theoretically optimal control result is often not significantly better than the pragmatic "good" solution. Instead, the reason for the rise in use of optimization methods has to do with the need to employ more powerful tools for incorporating complex constrains and dealing with multiple inputs and outputs, as well as multiple competing control objectives. The layering approach illustrated in Figure 2 and in Reference [8] naturally enables the use of such methods.

Figure 3 illustrates how such decomposition can be mapped to a power system infrastructure.

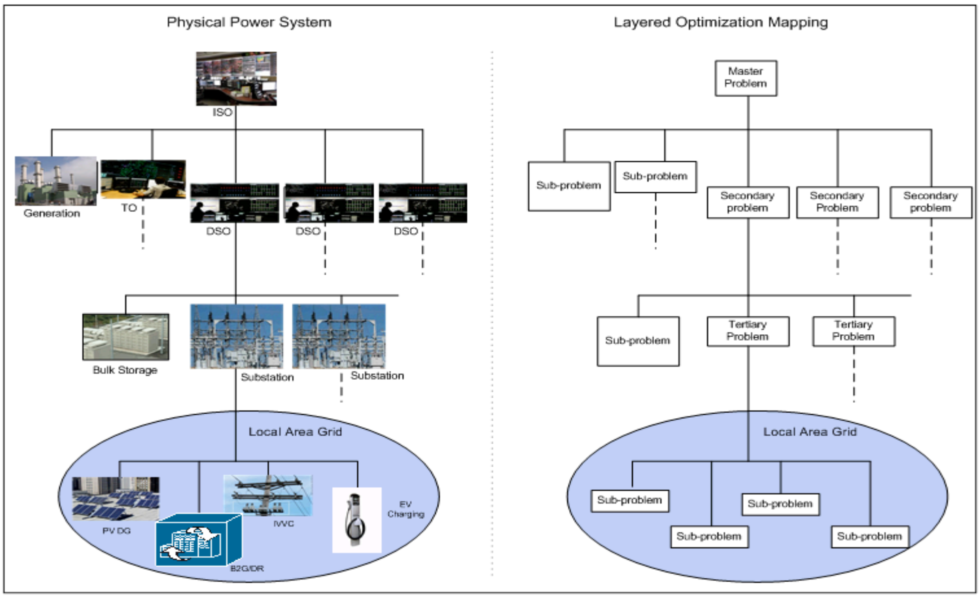

Figure 3. Example Mapping of Optimization Layers onto Power System Infrastructure

At each level in the multi-layer optimization, the appropriate organization, system, or device solves its own optimization problem, but in accordance with signalling 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.

Changing Role of the Distribution (DNO) Control Centre

The traditional distribution control centre has been the hub of control, for distribution system operators, with human operators very much in the loop. This mode of operation is not sustainable going forward in a grid environment where latencies are two orders of magnitude shorter than has been true in the past, and where the number of devices is exponentially greater than in older systems. Consequently, changes in control systems are needed and these bring some changes in control centre functions and architecture. In the distributed control model, less central control computing power is needed since computing is decentralized but new functions such as control application store and remote management, zero-touch deployment, and distributed database operation are needed instead.

Control centres that are part of a wide area coordination system will also have their own coordination nodes with southbound interfaces to the next level node (say, at primary distribution substations), as well as a northbound secure real time link to the next upper level coordination node.in that sense a control centre will not be simply the top of a hierarchical control tree, it will be a node in a wide area coordination network, but with the responsibility to perform control based on local requirements, constrains and goals within the coordination framework. We may consider that the control centre itself has been virtualized and exists in a distributed form. The virtual control centre will still have elements in what was the traditional control centre facility, but will exist in extended form throughout the entire distribution grid. Data may be stored at various computing nodes in the distribution grid instead of at a central data store and analytics, decision support tools, and control processes will access this distributed database in a manner that is transparent to the system operator.

All of the above means that future power grid control centres may shift from being intensive human-in-the-loop control systems to being control system management centres, with some familiar tools and some newer ones. The role of the system operator will still exist but will shift from a combination of system supervisor and inside the loop controller to an almost entirely supervisory role as regards grid control but still be a controller as regards management of the control system itself. The new function of managing distribution of control applications across a decentralized infrastructure will replace the direct specification of control actions.

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.

Future grid control architectural framework must provide the means to address needs such as federation, disaggregation, boundary deference, wide are coordination, as well as more traditional control system requirements. The layered optimization decomposition approach,, implemented in a hybrid of centralized and distributed elements can address these needs. This approach leads to changes in control centre functions and therefore also operational method changes, but these changes are incremental in nature and should not be seen as disruptive.

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