DEVELOPING A DISTRIBUTED INTELLIGENCE ARCHITECTURE FOR SMART GRIDS

Jeffrey D. TAFT, PhD
Cisco – USA
jetaft@cisco.com

Maik G. SEEWALD
Cisco – Germany
maseewal@cisco.com

ABSTRACT

Smart grids at scale will introduce a number of issues for which traditional distribution grid control and data system architectures are inadequate. In this paper we describe some of these issues and then introduce the concept of distributed intelligence to address the issues. Finally, we develop a high level architecture for a distributed intelligence system for distribution grids.

INTRODUCTION

Trends in development of smart grid concepts at the distribution level take somewhat different forms in Europe and North America, but the net results are the same: traditional approaches to distribution level communications and control are unlikely to be adequate for smart grids at scale. In both North America and Europe, deployment of smart meters is proceeding and will involve two-way communications to millions of endpoints. In some cases, the meters will also function as gateways into consumer premises to enable additional smart grid capabilities; in other cases gateways into premises will be done using communication paths parallel to the meter network or the meters will be connected to the gateways as other devices within the premises. In some cases, the meters will also functions as a fine sensor network attached to the distribution grid. In North America, there are typically a considerable number of distribution feeder devices that must be automatically controlled in a smart grid environment, including for purposes related to reliability. In parts of Europe, the reliability issue is not significant, but the integration of distributed generation is, as is the issue of providing various value-added energy services from energy service providers. Each utility has unique circumstances and requirements, but underlying them are a common set of advanced functionalities, and as smart grids reach scale, a common set of architecture issues.

Issues for Smart Distribution Grids

For smart grid at scale, a number of architectural issues arise, some well recognized, some not. These include data acquisition and aggregation from thousands or millions of endpoints; control command distribution to thousands or millions of endpoints; hidden coupling of applications through the physics of the grid; multi-objective control and control federation; control models; distribution grid state and communications for advanced distribution grids. The first two issues are widely recognized and have significant implications for smart grid communications, control, and applications architecture, which we will discuss shortly. The remaining ones are not as well understood since they do not manifest themselves at the scales on which smart grids have been tested or deployed to date. We briefly discuss the latter five points.

Hidden coupling – the hidden coupling problem arises through a failure to recognize that the physics of the power grid represents a coupling layer for smart grid applications and systems and that such coupling can lead to undesired consequences. An example of this is the coupling between volt/VAr regulation and either demand response or distributed energy resources. A recent analysis of such coupling [1] has shown that failure to coordinate the controls for these functions can lead to two kinds of problems: reduced effectiveness of the demand response application, and violations and breaker trips on the distribution circuits involved. As smart grids increasingly add functions that distribution grids were not originally designed to support, such interactions will continue to mount up and will themselves become more complex, meaning not just two-way interactions, but potentially N-way interactions. When aggregations of secondary loads or distributed energy resources become large enough, stability at the transmission level can be threatened [2]. Short of such effects, engineers who have examined the issue anticipate severe difficulties at the distribution level. A recent paper from the IEEE Working Group on Distributed Generation Integration documents a wide variety of undesirable interactions involving uncoordinated grid protection and control systems with distributed energy resources [3].

Multi-objective control and federation – as smart grid applications proliferate, the sharing of infrastructure, combined with the hidden coupling issue just discussed, lead to the recognition that distribution control will become multi-objective, multi-controller control. Given this, proper control requires control federation, which is the integration of multi-objective controls that use the same control devices or control the same system to different ends, but in a unified, non-conflicting fashion. This is already widely practiced in the form of an elementary smart grid function: integrated volt/VAr control. In this approach, substation Load Tap Changers (LTC's) and capacitor controls are coordinated to provide voltage regulation, unity power factor, and/or conservation voltage reduction. The interaction of voltage regulation with VAr control via electrical physics and topology of the grid led to undesirable excess operation of LTC's when the two types of control were not coordinated. On a larger scale, federation means the integration of multi-objective controls that use the same control devices or control the same system to different ends, but in a unified, non-conflicting fashion.

<u>Control models</u> – trends in distribution control involve both centralized forms, such as Distribution Management Systems (DMS) and distributed forms that rely upon more or less traditional thinking about measurement and control, with foundations in control theory and power systems design. Additionally, a newer group of models are emerging that are characterized by the distribution of minimal content control signals and no general availability of grid state at the control edge devices. These approaches go by various names, including Transactive Control [4], Distribution-Locational Marginal Pricing (D-LMP) control [5], and Adaptive Load Management (ALM) [6], but all use similar reduced information sharing approaches to attack scalability and keep communication bandwidth requirements low. Figures 1 and 2 illustrate these control models.

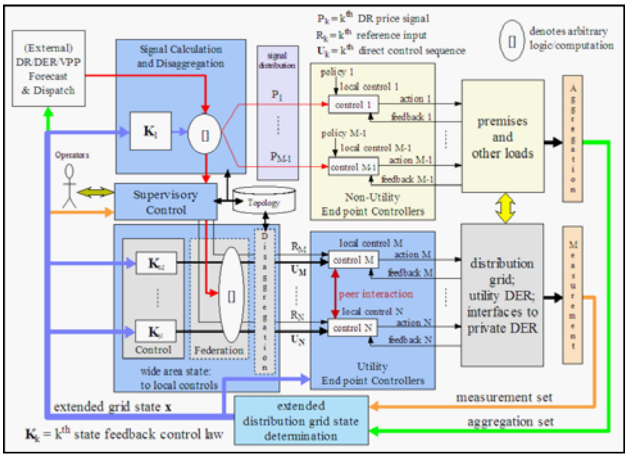

Figure 1 Classical (Type 1) Control Model

The Type 1 Control Model presumes the ability to distribute information widely throughout the control system, including complex control commands and control sequences, as well as measurement data. This aspect, combined with global grid state and peer interaction, means that control architecture based on the Type 1 Model can support arbitrarily complex control actions. It also means that such a control system requires significant communications and network management capabilities. Software development can be complex (such as with a DMS), but user interfaces can be domain-focused.

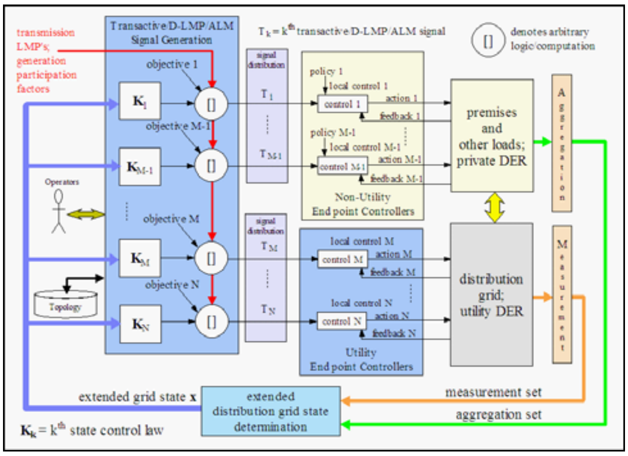

Figure 2 Emerging (Type 2) Control Model

The Type 2 Model uses extended grid state determination based on grid measurements and premises aggregations in the same way as with the Type 1 Model. However, grid state is not widely available in this model, as it can be in the Type 1 model. Instead, only the scalar control signals are distributed to end point controllers. Each scalar signal may be any of the following:

- a pricing signal
- a set point for a local controller
- a control law selector or adaptation parameter
- a performance objective (mixture of grid state and objective function)

In the Type 2 Control Model, control end points have built-in control laws and possibly policies, just as with Type 1, but no direct access to grid state, since grid state is mixed with objective functions and LMP values in a non-reversible manner. Transactive signals do not have the same value everywhere in the grid and must be distributed according to grid topology. In a few Type 2 control models, distributed nodes may interact in a peer-to-peer fashion, but generally, this is not the case. It does suggest however, that there will be an eventual hybridization of these two models.

<u>Distribution grid state</u> – smart grid functions require much information about the grid and its condition, far more than has been necessary for traditional distribution grids. The exact nature of the information depends on the specifics of the smart grid functions being implemented, and so varies by region and utility. We can, however, describe the entire information set collectively. To do so, we employ the concept of extended distribution grid state. The processes for grid measurement and DER aggregation contribute to the process of grid state determination (as opposed to state estimation). In the context of transmission, grid state involves voltages, currents, phase angles and power flows.

For distribution, we retain these but extend the definition considerably to cover other elements of importance such power quality state, component stress states, circuit and device thermal states, and topological states. Much of grid state is determined by measurements made on the grid itself.

As shown in the control models of Figures 1 and 2, the processes for grid measurement and DER aggregation contribute to the process of *grid state determination*. At the transmission level, grid state estimation is common, but at the distribution level, we must employ much more measurement (perhaps combined with some preferably small amount of estimation and forecasting,) than we would at the transmission level. This process includes calculating circuit parameters (system identification) along with electrical states.

Communications for advanced distribution grids – while the control models of Figures 1 and 2 differ in requirements for control command and state distribution, both have significant needs for data collection and aggregation, which is why networking is such a crucial element of smart grid design. While many forms of communication networking have been applied in power grids, going forward, the only practical approach for smart grids is the use of packet switched networks and IP. Given the number of endpoints likely to be involved, IPv6 is clearly to be preferred. While physical layers will differ, at layers 2 and above packet switching and IP will predominate. The advantages of IP-based packet switching networks are clear:

Requirement	IP Capability
Interoperability across multiple vendors	Open standards-based
Protect data and system integrity	Built-in security measures, services, and tools
Support for many types of media	Layered structure for media independence
Rapid collection of massive amounts of data	High performance and congestion management
Connect millions of devices	Practically unlimited scalability with IPv6
Rapid response to bursty event–related message data	Ability to prioritize traffic (QoS)
Arbitrary dynamic communication paths	Advanced packet-based protocols support any form of logical network, as well as sophisticated dynamic routing
Convergence of multiple existing networks	Proven migration path from multiple proprietary protocols to IP networks

Distributed Intelligence Architecture

As smart grids evolve to provide pervasive real-time monitoring and control of the power grid over a robust communication network, there will be an increasing need to adopt a hybrid approach of centralized and distributed control and embed distributed intelligence into the communication network. A purely centralized control approach will reach limits in its capability to support use cases that affect grid stability such as integration of renewables and micro grids due to latency, data management, and robustness issues. Distributed intelligence can provide a number of advantages: scalability, latency minimization for real time functions, robustness, survivability and graceful degradation in the presence of component or subsystem failure, incremental implementation and expansion, and flexibility to adapt to new functions and application. The two control models mentioned earlier can have either centralized or distributed implementations, but in practice the issues of scale, latency, and fault tolerance become so dominant when smart grids reach useful sizes that control, data management, and analytics inevitably must have distributed implementations, albeit, with central management and supervision.

Architecture for the smart grid distributed intelligence platform consists of three layers: the application development/test/security signing layer, the run time application management layer which resides in the control center, and the distributed nodes, which reside at various places in the grid. Figure 3 illustrates this architecture.

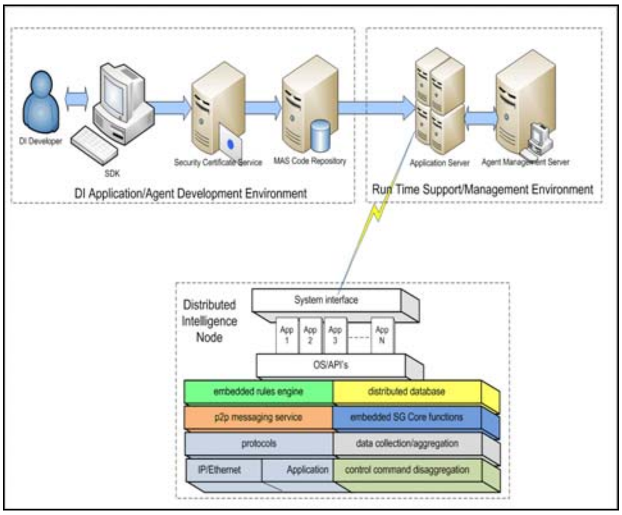

Figure 3 Smart Grid Distributed Intelligence Architecture

The distributed intelligence nodes contain standard network routing functions; applications protocols as well as networking protocols, including protocols for legacy devices; data acquisition and aggregation; control command disaggregation; special purpose processing for grid data; distributed data persistence; event management; security and network management; peer to peer messaging and core function class implementations with API access for smart grid applications. The embedded core function classes provide basic smart grid capabilities useful to a wide variety of smart grid applications, rather in the manner of an operating system providing core low-level functions to ordinary data processing applications. The core function classes include:

- grid state determination
- low level control
- fault intelligence
- outage intelligence
- power quality measurement
- remote asset monitoring

By incorporating these functions directly into the distributed intelligence framework, it becomes a platform upon which smart grid applications can easily be built, including applications that have yet to be conceived.

The places where we wish to locate distributed intelligence nodes include primary distribution substations, secondary stations in European grids, and at or near control and sensing devices on feeder circuits in North American style grids, as well as in customer premises that are linked to the grid via such capabilities as DER, micro grids, and Demand Response. Remarkably, these are the very places that we need smart grid communication devices. This leads to a significant conclusion about where the distributed intelligence nodes should reside: **the smart grid communication network is an effective location to embed distributed intelligence** because it is pervasive, has visibility of the data needed for distributed analytics and control and can enable the inter-element messaging between various sensors, applications, and actuators within the grid.

Conclusions

We have seen that distribution control models are evolving in complexity and that ubiquitous digital communication networking is a key enabler for smart grids at scale. We recognize that the problems that come with smart grids at scale are addressable by a hybrid of centralized and distributed intelligence. Finally, we have seen that the preferred locations for distributed intelligence nodes coincide nicely with the locations of digital networking devices, needed in the grid, making it logical to consider a merging of the two.

REFERENCES

[1] Medina, Jose, Nelson Muller, and Illya Roytelman, “Demand Response and Distribution Grid Operations: Opportunities and Challenges”, *IEEE Transactions on Smart Grid.* vol. 1, no. 2, 193-198

[2] Bollen, Math and Irene Gu, 2006, *Signal Processing of Power Quality Disturbances*, IEEE Press, John Wiley and Sons, Inc., Hoboken, New Jersey, USA, 33-35.

[3] Walling, R.A., et.al., July 2008, “Summary of Distributed Resources Impact on Power Delivery Systems”, *IEEE Transactions on Power Delivery*, vol. 23, no. 3, 1636-1644

[4] Hammerstrom, Donald, et.al., 2009, “Standardization of a Hierarchical Control System”, *GridWise Architecture Council Grid-Interop 2009*, Denver, CO, USA [link to paper]

[5] Heydt, G. T., December 2010, “The Next generation of Power Distribution Systems”, *IEEE Transactions on Smart Grid*, vol. 1, no.3, 225-235.

[6] Joo, Jhi-Young, and Maria Ilic, April 2010, “A Multi-Layered Adaptive Load Management (ALM) System: Information exchange between market participants for efficient and reliable energy use”, *Transmission and Distribution Conference and Exposition, 2010 IEEE PES*, New Orleans, LA, USA.