A New Multi-Level Electric Grid Architecture Designed for Massive DER Penetration

Robert H. Lasseter, *Life Fellow, IEEE* Thomas M. Jahns, *Fellow, IEEE* Bruce C. Beihoff, *Sr. Member, IEEE* Gary Radloff Victor M. Zavala, *Member, IEEE*

***Abstract*—A new electric grid architecture named the Dynamic Distribution System (DDS) is proposed with the express purpose of making the electric grid compatible with massive penetration of distributed energy resources (DERs). The DDS architecture is based on the concept of aggregating DERs into progressively larger groups in a multi-level configuration, beginning with functional clusters at the lowest level that could be implemented as microgrids. The distribution system controllers serve as market makers to provide DERs a means of competitively selling their excess electricity while also fulfilling their responsibilities to deliver ancillary services when needed. The DDS architecture offers several valuable advantages as a result of accommodating massive DER penetration including higher renewable energy usage with lower power flow volatility, as well as higher grid resilience due to the ability of the functional clusters to operate autonomously when necessary.**

***Index Terms*—Distributed power generation, microgrids, power distribution, model predictive control, power grids, power system control, power system economics, power system reliability, power system stability, renewable energy sources**

I. Introduction

Ever since the electric grid first matured in the late 1800's, its architecture has been based on the use of large electric power generation plants with power ratings that today typically exceed 1 GW. These high power ratings have been dictated by the prevailing economies of scale associated with the adopted technologies for electric power generation, including fossil fuel combustion, nuclear fission, and conventional hydropower.

However, important forces are at work that hold the potential to result in significant changes in both the mix of sources and the sizes of future electric power generators. Global concerns about the increasingly urgent need to dramatically reduce greenhouse gas (GHG) emissions are creating a potent cloud of uncertainty about the future construction of large coal-burning power plants in several countries including the United States [1]. Increasing worldwide attention has been focused on alternative energy sources for electric power generation that either reduce or eliminate GHG emissions, significantly boosting the installation of both natural gas and renewable energy (RE) power sources around the world.

It is widely recognized that large-scale RE power generation introduces significant new challenges for the operation of the future electric grid because of their intermittency and their associated deficiencies as dispatchable power resources. Nevertheless, 2013 was the first year when the world installed more new nameplate power generating capacity drawn from renewable energy sources (143 GW) than from fossil fuel sources (141 GW) [2]. A large percentage of the solar photovoltaic (PV) power installations are in the form of distributed generation (>50% in Germany in 2012 [3]), confirming that distributed energy resources (DERs) are on track to because a growing fraction of the world's electric power generation capacity during the coming years.

The prospect of the installation of very large numbers of distributed power generators in the future, many based on intermittent RE sources, is raising serious concerns in the power engineering community about the ability of today's electric power system to adapt to such a major change in its basic architecture. These include concerns about the fundamental controllability and stability of future utility grids if the penetration level of distributed generation grows significantly in the future, particularly if these DERs are not directly controlled from a central source [4].

Beyond the technical issues raised by high penetrations of distributed generators, there are serious questions about the compatibility of very high numbers of DERs with the current configuration of utility electric grids. Concerns include their compatibility with existing protection systems as well as their economic compatibility with the long-standing electricity business model based on large regulated electric utility companies. Existing federal and state regulations developed in the US over the course of the last 100+ years create major compatibility barriers since they did not contemplate highly distributed power generation. Aggressive initiatives are under way in several countries, including some states in the US such as California and New York, to rework their electric utility regulations to remove these barriers and actively encourage new DERs investments [5].

Taken together, the evidence highlights both the tremendous potential benefits of high penetration of distributed electric power generation and the major technical, regulatory, and economic obstacles it faces. These barriers threaten to significantly limit the penetration

Much of the microgrid work was supported by the Office of Electricity Delivery and Energy Reliability, Transmission Reliability Program of the U.S. Department of Energy and administered by the Lawrence Berkeley National Laboratory.

Em. Prof. R. H. Lasseter is with the Dept. of Electrical and Computer Engr. at the Univ. of Wisconsin – Madison. (lasseter@engr.wisc.edu)

Prof. T. M. Jahns is with the Dept. of Electrical and Computer Engr. at the Univ. of Wisconsin – Madison, Madison, WI. (jahns@engr.wisc.edu)

B. C. Beihoff and G. Radloff are with the Wisconsin Energy Institute at the Univ. of Wis. – Madison. (beihoff@wisc.edu, gary.radloff@wisc.edu)

Prof. V. M. Zavala is with the Dept. of Chemical & Biological Engr. at the Univ. of Wisconsin – Madison. (victor.zavala@wisc.edu)

of DERs unless major changes and adjustments are made in our current electric power grid to overcome them.

The objective of this paper is to present a new electric grid architecture that is designed to make the grid much more compatible with massive penetrations of DERs while retaining as many of the strengths of the existing electric power grid as possible. A feature of the new Dynamic Distribution System (DDS) architecture is its aggregation of DERs into progressively larger groups in a multi-level configuration that offers several appealing advantages including higher RE compatibility, lower power flow volatility, and higher grid resilience.

II. Background

A. Massive DERs Penetration Challenges

Using DERs in the distribution system reduces the physical and electrical distance between generation and loads. Bringing sources closer to loads contributes to enhancement of the voltage profile, reduction of distribution and transmission bottlenecks, lower losses, enhances the use of waste heat, and postpones investments in new transmission and large-scale generation systems.

A basic issue for DERs is the technical difficulty associated with the control of large numbers of distributed energy sources. This issue is complicated, but the call for extensive development of fast sensors and complex control raises serious concerns about grid robustness and resilience [6]. The fundamental problem with a complex control system is that the failure of a key control component or a software error could have major negative consequences for the grid's operating characteristics.

B. Microgrid Concept

A very different approach is to aggregate sources and loads in a microgrid using DERs that are capable of operating without a central controller. According to this approach, microgrid-based DERs are designed to respond to local events autonomously using only local information including electrical bus frequency and voltage amplitudes. For severe voltage drops, faults, blackouts, etc., the DERs together with their loads switch to island-mode operation using local information. This requires an immediate change in the output power control of the generators from a dispatched power mode to islanded operation that controls the voltage and frequency of the islanded section of the network in order to meet the demands of the islanded loads.

The requirements summarized in the preceding paragraph are embodied in the CERTS microgrid concept [7]. Original objectives of the CERTS microgrid concept included reduction of microgrid system cost and increased reliability using key features including plug-and-play functionality without communications. Plug-and-play concepts reduce engineering cost and errors since little site modification is required for different applications. Each CERTS device regulates voltage and frequency during both grid-connected and islanded operation. CERTS sources explicitly protect themselves from overloading during island-mode operation. Due to space limitations, interested readers are referred to publications that provide detailed analyses of the operating characteristics of CERTS microgrids and discuss a variety of laboratory and commercial implementations [8-10].

C. Beyond Microgrids

As DERs penetration into the distribution system increases, the complexity rises dramatically. This paper proposes the application of key microgrid concepts to break this complexity into more manageable electrical systems. That is, the microgrid concept of aggregating sources and loads into a combined system can be broadened and extended in a manner that provides significant value for managing the complexity challenges. More specifically, the concept of a *functional cluster* has been developed as an extension of the original microgrid concept as a means of providing additional value to distribution systems in a variety of ways in addition to reducing complexity.

A functional cluster consists of combinations of physical devices including both DERs and loads, discussed in more detail in Section III. Importantly, these DERs and loads are capable of operating autonomously inside the functional cluster whenever appropriate or necessary due to disconnection from the grid or loss of communications with other control authorities. The CERTS microgrid is just one example of a functional cluster that is capable of seamlessly regulating its voltage and frequency when islanded, as discussed above.

Under normal conditions, the DERs and loads comprising a functional cluster operate connected to the grid under the supervision of a local controller that is designed to balance loads and sources in its cluster within the limits of its available resources. It also acts as aggregator that presents its constituent DERs and flexible loads to the rest of the distribution system as a single integrated DER. By communicating with other controllers as described in the following sections, the cluster controller can make the cluster's excess generating capacity available to the grid for dispatch or for delivery of ancillary services.

D. Proposed Architectural Approaches

The use of architectural design has become one our modern era's most successful and prevalent techniques for dealing with the growing complexity of large systems. Over the past 10 years of renewed interest in grid modernization, the attention being devoted to grid architecture has grown considerably. This is reflected in both the growing numbers of technical publications devoted to this issue as well as the founding of the industry-based Gridwise Architecture Council by the US Department of Energy [11].

In this paper, architecture is defined as "the interrelationships of the functions and structures comprising a system; and, the evolutionary paths of change available to the system with the passing of time." Many of the other large manmade systems developed over the past sixty years have been made possible by the application of this analytical design approach, including the data and communication networks, aerospace systems, maritime systems, defense systems, automation and process control systems, etc. These massive human-built systems have greatly varying fundamental physics, use cases, operating modes, and failure modes.

The unique features associated the electric grid system can be highlighted by both its demanding requirements (e.g., 99.999 availability and low harmonic distortion of the line voltages) and its special constraints (e.g., cyclical synchronicity of all parallel generators, and 99.9% real-time balance of power generated and power consumed). Recognizing these demanding requirements/constraints and the emerging challenges for the grid described in the introduction, three major architectural design principles have emerged as prime candidates to guide development of the future grid architecture.

Top-Down Control utilizes one or more central controllers operating at the very top of the control hierarchy. The top-down control approach can be characterized as follows:

Pros: (i) Given the power law increase in processor power and the ability to network controllers together as integrated super-controllers, any scale of system can be managed by bringing all of the critical sensing and actuation signals back to the main controller; and (ii) These centralized controller(s) have the least latency between sub-processes necessary to implement and coordinate thousands of control functions, and they can be configured entirely from end-to-end by direct software updates;

Cons: (i) Central points of failure with large system impacts are major risks; (ii) Huge numbers of cables or wireless media ports have to be made available to the central controller and run long distances through complex physical environments; (iii) Computational scaling rapidly becomes a daunting complexity problem when sensing and actuation points range into the tens of thousands (as would be the case in most modern distribution systems) and extend over thousands of possible physical paths from periphery to central station.

Bottom-Up Control is based on the fundamental control principle of "agent autonomy", concentrating all of its functional capability in the local controller. These controllers would have similar functional configurations, with each having the ability to adapt its control law to the local conditions read from the power line and the local environment. The only communication between controllers would be through their effects on the power flow, voltage, and frequency of the distribution system interconnections.

Pros: (i) No single point of failure; (ii) Fastest response to local transients of source and load; and (iii) Easy scalability to any combination of small or large load groups, feeder configurations, as well as generator and load sizes.

Cons: (i) No simple way to have both optimum stability and power flow across larger networks; and (ii) Large group coordination of dispatch or reserve power is difficult.

Hybrid (Middle-Out) Control attempts to combine the best characteristics from the preceding two architectures and blend them into an optimum combination. This architectural approach has also been referred to as multi-level, hierarchical, or multi-scale. This control architecture consists of multiple levels of controller functions. For purposes of illustrating this concept, this architecture begins at the bottom with functionally-grouped loads, sources, and storage on feeders (or clusters) that are managed by a *Functional Cluster Controller* during both grid-connected and islanded operation. Moving up from the cluster level, the second (middle) level is the substation controller that handles slower setpoint and dispatch signals from multiple cluster controllers. The highest-level controller in this hierarchy is the distribution system controller that handles aggregations of even slower signal updates from a number of substation controllers for purposes of optimum flow dispatch and economic dynamic transaction execution.

Pros: (i) No single point of failure; (ii) Fastest response to local transients of source and load; (iii) Easy scalability to any combination of load groups, feeder configurations, generator and load sizes; and (iv) Highest capability to integrate efficient scalable optimization algorithms, bullet-proof auto-stabilization, and protection functions.

Cons: (i) Requires more sophisticated standards for interface and operability than the other two approaches; and ii) Concerns about the maturity of distributed control algorithms to insure system stability under all conditions.

III. Dynamic Distribution System (DDS)

A. DDS Architecture Concept and Features

Recognizing the strengths and limitations of alternative power grid architectures discussed in Section II to overcome the obstacles to massive DER penetration, the Dynamic Distribution System (DDS) concept is proposed as a promising architectural approach for achieving the desired objective. It purposely retains many of the attractive features of the existing electric power grid architecture but introduces important modifications that are tailored to fundamentally improve its compatibility with large numbers of distributed generators. A specific objective when developing this DDS architecture has been to find innovative approaches that make it possible to combine the best characteristics of centralized power plants and autonomous personal power plants into the same grid architecture.

Referring to the DDS concept diagram in Fig. 1, the large numbers of DERs present in each *Distribution Region (DR)* are aggregated into many *Functional Clusters (FCs)*. These FCs are managed by a multi-level control structure consisting of multiple *Mid-Scale Controller (MSC)* units and a *High-Scale Controller (HSC)* assigned to each distribution region. The HSC and the MSCs together play a major role in balancing the sources and loads inside their distribution region with the objective of minimizing the volatility at the transmission/distribution (T/D) interface. In addition, the distributed HSC/MSC controllers serve as a market provider (MP) within their DR. The HSC plays key aggregation roles by representing its distribution regions in market transactions with the *Transmission System Operator (TSO)* that already exists at the transmission level, and organizing its DERs to deliver all required grid ancillary services including operating reserves.

This DDS architecture has been specifically formulated to deliver high-value dynamic functions at the distribution system level that enable it to deliver ancillary services and reduce volatility at the T/D interface while preserving the ability of functional units, substations, and distribution

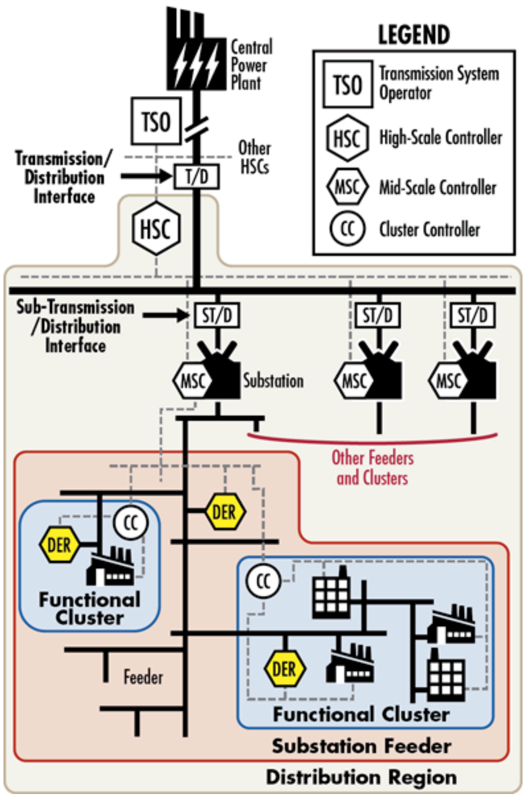

Fig. 1 DDS architecture concept diagram.

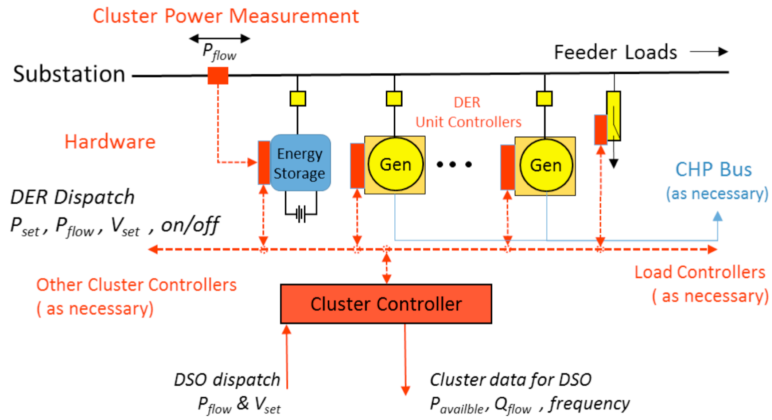

Fig. 2 Functional cluster configuration

regions to operate autonomously if communications are lost. It is important to note that Fig. 1 was formulated to introduce the basic concepts of the DDS architecture. A broad variety of system configurations is possible to satisfy local requirements, including opportunities for having more than one level of mid-scale control to provide the necessary aggregation and control functions for larger power systems.

Despite the major departure of the DDS concept from the standard utility architecture with respect to the role of the distribution system, it is important to emphasize that the DDS concept is capable of coordinating large numbers of DERs and flexible loads with existing large central power plants. The goal of the DDS concept is to make it possible for large power plants to do what they do best: deliver bulk power generation as efficiently and cleanly as possible with minimum need for set point variations.

Key components of DDS architecture shown in Fig. 1 are described briefly as follows: *Functional Clusters and Physical Devices*: The basic building block of the DDS architecture is the functional cluster that consists of combinations of physical devices including both DERs and loads. The DERs are assumed to take a wide variety of forms including renewable energy sources (e.g., solar, wind), conventional sources (e.g., natural gas gen-sets with internal combustion engines (ICEs)), energy storage (e.g., batteries, flywheels), and loads (both flexible and conventional). It is assumed that DERs that generate large amounts of heat in addition to electricity (e.g., ICEs and fuel cells) will be implemented with Combined Cooling, Heating, and Power (CCHP) capabilities whenever possible in order to significantly increase their overall operating efficiencies in buildings and factories.

The DERs and loads comprising a functional cluster operate under the supervision of a cluster controller (CC) as shown in Fig. 2. The cluster controller is designed to balance loads and sources in its cluster within the limits of its available resources. It also acts as aggregator that presents its constituent DERs and flexible loads to the rest of the distribution system as a single integrated DER/load. The functional cluster is designed to report its real and reactive power export availability to the mid-scale controller (MSC) and then receive and act on power dispatch commands transmitted by the MSC. Although the number, ratings, and configuration of the DERs and loads comprising a functional cluster in the DDS architecture are very flexible, it is convenient for this introductory discussion to associate each functional cluster with a separate feeder in a substation grid as indicated in Fig. 1.

It is important to emphasize that the functional cluster, as conceived, can take many different forms. For example, one promising implementation of a functional cluster is a CERTS microgrid introduced in Section II that is capable of operating autonomously with plug-and-play distributed generators and loads while seamlessly regulating its voltage and frequency. Although this autonomous operation capability is appealing, a functional cluster is not required to be capable of islanded operation, so a collection of more conventional distributed generators and loads operating under the supervision of a shared controller also qualifies as a functional cluster.

There are no limits set on the number of distributed generators, energy storage units, or loads within the boundaries of a functional cluster. A cluster might be confined to a single building that could take the form of a private residence, an apartment building, a retail store, a factory, or a hospital, to name just a few examples. The DDS architecture is also intended to encourage entrepreneurs to invest in the construction of their own functional clusters consisting primarily of distributed generators and energy storage units that are designed to compete for the sale of electricity and heat to other buildings (i.e., functional clusters) in the same local region.

Mid-Scale Controller (MSC) and High-Scale Controller (HSC): The combined distributed control actions of the

MSC and HSC play a critical role in the DDS architecture by working to balance the sources and loads within a distribution region while also serving as a market provider (MP) inside each distribution region. In the process, the HSCs and MSCs fulfill roles that have been the exclusive province of the Independent System Operators (ISOs) in the prevailing utility system model. For convenience, it will be assumed that each substation is equipped with its own MSC, giving the MSC the functionality of a substation controller. However, the DDS concepts can flexibly accommodate configurations with multiple substations assigned to each MSC as well as other variants.

The HSC is given responsibility for overseeing all of the MSCs in its distribution region, giving it a role that has been referred to as an Independent Distribution System Operator (IDSO) [12]. Under normal operating conditions, the automated MSC communicates with all of the cluster controllers inside its assigned substation as well as the HSC in order to fulfill its load tracking and balancing obligations as its highest priority. An additional key responsibility of the MSC is to respond to HSC requests for ancillary grid services by marshaling the aggregated power delivery capabilities of the DERs connected to its feeders to promptly fulfill these requests, including operating reserves.

As noted above, the DDS concept makes another major departure from conventional utility systems operation by giving the HSC/MSC distributed controllers the responsibility of serving as a market provider that manages energy transactions between buyers and sellers inside their distribution region. The goal of this market is to reward stakeholders for installing microsources and flexible loads, reducing their payback times and encouraging them to install more units. Although the presence of this market inside the distribution system is a distinguishing feature of the DDS architecture, a detailed discussion of the key features and special challenges associated with this marketplace lies beyond the scope of this paper. Interested readers are referred to other publications for more details about this critical topic [13].

The HSC/MSC controllers serve critical roles as aggregators, similar to the cluster controllers, representing all of the DERs and flexible loads in their distribution region in interactions with the TSO as if they were a single integrated DER/load. A key performance criterion for each HSC and MSC under normal operating conditions is to minimize the volatility of the power flow at the distribution region's T/D interface with the transmission system, a source of major utility operational benefits that is highlighted in the next section. The HSC and MSCs also share the same objective of delivering robust autonomous operation that was discussed above for cluster controllers in the event of loss of communications with the next higher level in the distributed control hierarchy.

For the purpose of discussion in this paper, it will be assumed that the HSC and the constituents of its distribution region operate in the sub-transmission level of the DDS architecture. It is anticipated that high-power DERs such as multi-MW wind and solar PV farms may appear at this sub-transmission level, interacting directly with an HSC as a distribution region power source rather than being assigned to an MSC in a substation. As noted above, many variants in the size and position of DERs in the DDS architecture are possible that fall beyond the scope of this paper.

Transmission System Operator (TSO): The TSO plays much the same role in the DDS architecture that it does in the conventional utility system in the form of the Independent System Operator (ISO). That is, the TSO serves as both the balancing authority and market provider at the transmission system level. It also plays the key role of managing the ancillary services in its transmission region by assessing needs and, ultimately, issuing dispatch commands to the generating sources in its region. The major change in the TSO responsibilities in the new DDS architecture compared to the current utility grid is that it now has access to all of the DERs in its transmission region that will contribute to accomplishing both its balancing and ancillary service functions. It accesses these DERs solely by communicating with all of its connected HSCs; it never "skips tiers" and communicates directly with either the MSCs or the functional clusters themselves.

The TSO also retains its current responsibilities as a market provider for all of its connected generating sources that now include all of the DERs represented in aggregated form by their associated HSCs in addition to the large central power plants that exist in today's power grid. Although the number of TSO-managed generating nodes will be significantly increased compared to today's utility system, the level of volatility and magnitude of the ramping reserves requirements that each TSO must handle is projected to be greatly reduced compared to today's transmission system because of the significant reductions in volatility that each MSC and HSC is responsible for achieving at the T/D interface.

IV. DDS Benefits

The DDS architecture based on functional clusters radically changes the role of conventional distribution systems, empowering them for the first time to act as both balancing agents and market providers for large numbers of DERs within their boundaries. The key role of the distribution system in the new DDS architecture shifts control responsibilities away from the traditional top-down hierarchy used for the past 100+ years toward a more bottom-up distributed control system.

A summary of the key benefits provided by the DDS architecture as a particularly promising approach to accommodating massive penetration of DERs includes:

- Introduction of distribution system intelligence/control using a scalable, multi-level distributed control system that is highly adaptable for all grid use topologies.
- Major reductions in volatility at the transmission/ distribution interface.
- Compatibility with autonomous operation of the DERs inside functional clusters, providing plug-&-play capabilities and superior resiliency.
- High compatibility with renewable energy sources and flexible demand response loads.

- Compatibility with convenient placement of DER micro-sources in locations that include many customers for waste heat, significantly boosting the grid system efficiency and improving DER affordability.
- Designed to introduce robust market mechanisms into the distribution system that provide critical financial incentives for stakeholders to expand DER and RE penetration.
- High level of compatibility with the current electric grid architecture that make it much easier to conceive of evolutionary scenarios for expanding the adoption of the DDS architecture.

In summary, the DDS architecture holds major promise for transforming the installation of very large numbers of DERs (RE-based and otherwise) from a major potential liability into a critical asset for utilities and their customers.

V. DDS Current Status and Remaining Challenges

The preceding sections have presented material that makes a case for the DDS architecture as a promising approach for achieving massive DER penetration in the future electric grid. In this section, attention is focused on the key techno-economic components that distinguish this architecture from the status quo and their current development status and remaining challenges. Space limitations in this paper prevent a thorough examination of this important topic, but three of the most important distinguishing techno-economic features of the DDS architecture will be addressed: 1) Functional cluster and microgrid technology; 2) Multi-level hierarchical control paradigm; and 3) Transactive energy market algorithms.

A. Functional Cluster / Microgrid Technology

Of the three selected DDS architecture components selected for closer examination, the technology of functional clusters has received the most development attention to date, particularly in the context of microgrids. More specifically, the microgrid has become a widely-accepted paradigm for implementing DERs and is currently the subject of major R&D and demonstration projects around the world.

Taking the CERTS microgrid concept as an example, this technology has progressed successfully during the past 15 years through the initial stage of university laboratory concept demonstration R&D (10 to 30kW) in the early 2000s [14], to early field testing and demonstration at the American Electric Power (AEP) test site (100 to 200kW) during the period 2005-12 [15], and, most recently, a full-scale field demonstration at the Santa Rita Jail in California (>2MW) that was commissioned in 2013 and continues in operation today [16].

B. Multilevel Hierarchical Control Paradigm

Although a variety of alternative control approaches are candidates for implementation in the DDS architecture, attention is focused here on Model Predictive Control (MPC) as one of the most promising candidates. MPC is an optimization-based control technology that enables direct handling of nonlinear multivariable system interactions, physical constraints, and economic objectives. Most notably, it is possible to derive MPC formulations capable of simultaneously optimizing economic performance while providing stability and robustness guarantees [17].

In a grid setting, MPC takes the function of a supervisory energy manager that seeks to maintain voltage and frequency stability while dispatching demand and generation resources in a cost-optimal manner. The MPC formulation can incorporate detailed physical descriptions of the system that capture generator dynamics and power flow equations.

The challenge is to create a sensible MPC architecture that balances autonomy and central performance. A multi-level MPC paradigm is proposed to accomplish this objective. The key idea is to construct a hierarchical control structure of different resolutions. Consider, for instance, a three-level system consisting of a low-scale, mid-scale, and high-scale levels. The low-scale level would be comprised of individual MPC agents that manage their own local functional cluster. The mid-scale level would be comprised of MPC control agents where each agent manages a cluster of functional clusters. At the mid-scale level, MPC agents use lower-complexity aggregated representations of the clusters. At the top of the hierarchy is the high-scale level comprised of a central MPC agent that manages clusters of mid-scale MPC control agents.

While this architecture is intuitive, it is necessary to determine what would be an appropriate communication protocol between MPC agents within each level and across hierarchical levels. To do so, it is possible to use dual information. The idea is similar in principle to Lagrangian dual decomposition [18] but applied in a hierarchical manner. The high-scale MPC controller will compute optimal policies for supply and demand that balance the aggregated network and Lagrange multipliers (dual variables) for the flow exchange between nodes would be computed. This information can be interpreted as prices for energy exchanged. The dual information will then be passed to the mid-scale controllers, which will seek to dispatch supply and demand for their local network and will use the dual information of the high-scale controller to balance exchanges between mid-scale controllers. Each mid-scale controller will compute dual information for its local network that can also be interpreted as price for energy exchanges in its local network. Mid-scale dual information within each network will then be passed to the lower layer in the hierarchy to coordinate exchanges between low-scale controllers.

It should be noted that this approach can be generalized to more than 3 levels. However, it must also be recognized that this scheme would propagate errors down the hierarchy that result from the approximate representations of the clusters used in higher hierarchical levels. Such errors could induce instability and poor performance of the entire system. The key observation is that dual information obtained at higher levels can be refined at lower levels by performing Lagrangian dual decomposition steps. One could thus interpret the dual information of higher levels as warm-starts or guesses for dual variables that are refined on-the-fly at each level. A similar approach to create hierarchical MPC architectures that manage multiple time scales has been recently proposed [19].

A key issue is to ultimately ensure that the entire grid system remains stable. To achieve this, one could ensure that each functional cluster is dissipative by design and that the topology of the network is such that the coupled system is dissipative. This would guarantee the existence of a central Lyapunov storage function that would in turn guarantee that the central system can be optimized for economics while maintaining stability [17].

The central Lyapunov storage function can be monitored to guide refinement of dual information. In other words, the key is to interpret the hierarchical scheme proposed as an iterative scheme that seeks to solve the centralized MPC controller problem to a sufficient level of optimization that guarantees central stability. If a central Lyapunov storage function cannot be guaranteed to exist (i.e., a change of topology due to line failures), one could resort to alternative MPC schemes that use auxiliary stable MPC controllers to guide stability [20]. For instance, one could introduce stabilizing constraints that ensure that each low-scale MPC controller achieves descent on its local Lyapunov storage function at each time step.

C. Transactive Energy Market Algorithms

There is no escaping the conclusion that the success of the DDS architecture is dependent on the successful development of robust market algorithms for distribution systems. These market algorithms will be responsible for financially rewarding DER owners for the electricity that they export while simultaneously fulfilling responsibilities for minimizing upstream volatility and providing the necessary services to insure tight regulation of the grid voltages and frequency under all normal and abnormal operating conditions. Fortunately, the continuous growth of distributed energy resources is already creating new markets and influencing the shape of future electric grid design.

The term transactive energy is now being applied to the growth of DER in reference to techniques for managing the generation, consumption or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints, according to the Gridwise Architecture Council [21-22]. With a focus at the distribution level of the grid, transactive energy will build on the wholesale electric market-controls paradigm used to achieve economic efficiency and system reliability. Dynamic pricing is currently used in wholesale markets, and it is expected similar transactions will grow across the distribution/retail level.

The complexity of growing numbers of DER technologies and services combined with a similar exponential growth in dynamic economic transactions requires new thinking in architectures and energy business models to achieve both system stability and optimality. The key to achieving both system stability and optimality is linked with the DDS multi-level architectural approach and model predictive control.

Moving forward with continuous DER growth and foundational new paradigms for energy markets will require adaptability and flexibility not now found in the grid design and existing utility business models. Fortunately, the early stages of transactive energy can already be observed in some US energy markets with utility purchases of distributed grid services from DER providers as alternatives to traditional grid investments as currently under development in the states of California, Hawaii, and New York. Likewise, the continued growth of peer-to-peer transactions will occur as multi-user microgrids sell energy services to nearby customers across a utility distribution region. Furthermore, the increasing deployment of energy storage and dispatchable distributed generation creates new opportunities for local retail energy market sales.

VI. Conclusions

This paper has articulated a vision for an electric grid architecture that is specifically designed to both accommodate and encourage massive penetration of distributed energy resources in future electric grids of the developed world. While details of the Distributed Distribution System (DDS) architecture may reflect a pedigree linked to the electric grid architecture in North America, the authors believe that the majority of its key features can be translated to implementations that would be appropriate for application to large electric grids found throughout the rest of the world.

As presented in this paper, the heart of the DDS architecture concept lies in transferring key features that already exist in the current electric grid at the transmission system level down to the distribution system, transforming conventional distribution systems in the process. Key concepts governing the rationale, roles, and responsibilities of Independent System Operators and Regional Transmission Operators at the transmission system level today are replicated in scaled forms as the independent Distribution System Operators in the envisioned DDS distribution system. The ambitious goal is to design the DDS architecture in such a way that the success enjoyed by the ISO/RTO's today at the wholesale level can be duplicated inside DDS distribution systems at the retail level.

While some of the challenges that must be confronted by the DDS architecture concept are truly technical in nature, the biggest barriers to its ultimate success lie with the regulatory and business model obstacles that will have to be surmounted by *any* new electric grid architecture that attempts to change today's electric grid and its associated utility business structure in any substantial way. While such barriers and the prospects for overcoming them lie beyond the scope of this paper, there is no way to disguise how formidable they are.

Nevertheless, the stakes are too high to prevent the power engineering community from seriously exploring new ways to address the monumental societal challenges posed by the fundamental limitations of today's electric grid architecture. The search for better solutions must continue, and the DDS architecture offers a combination of benefits that are sufficiently intriguing to merit closer scrutiny.

References

[1] "FACT SHEET: Overview of the Clean Power Plan", US Envir. Protection Agency (EPA), https://www.epa.gov/cleanpowerplan/fact-sheet-overview-clean-power-plan .

[2] T. Randall, "Fossil Fuel Just Lost the Race against Renewable", Bloomberg News, Apr. 14, 2015: http://www.bloomberg.com/news/articles/2015-04-14/fossil-fuels-just-lost-the-race-against-renewables

[3] H.K. Trabish, "Why Germany's Solar is Distributed", Greentech Media, May 29, 2013, http://www.greentechmedia.com/articles/read/why-germanys-solar-is-distributed .

[4] "Potential Bulk System Reliability Impacts of Distributed Resources", North American Electric Reliability Corp. (NERC), Aug. 2011, http://www.nerc.com/docs/pc/ivgtf/IVGTF_TF-1-8_Reliability-Impact-Distributed-Resources_Final-Draft_2011.pdf .

[5] "Renewing the Energy Vision: About the Initiative", NY Dept. of Public Service, Jan. 28, 2016, http://www3.dps.ny.gov/W/PSCWeb.nsf/All/CC4F2EFA3A23551585257DEA007DCFE2?OpenDocument

[6] W. Bower, D. Ton, R. Guttromson, S. Glover, J. Stamp, D. Bhatnagar, & J. Reilly, "The Advanced Microgrid," Sandia National Laboratories, Report No. Sand2014-1535, March 2014.

[7] Lasseter, R.H., P. Piagi, "Microgrid: A Conceptual Solution", in *Proc. of IEEE PESC'04*, Aachen, Germany, 20-25 June 2004.

[8] R.H. Lasseter, J. H. Eto, B. Schenkman, J. Stevens, H. Volkmmer, D. Klapp, E. Linton, H. Hurtado, & J. Roy, "CERTS Microgrid Laboratory Test Bed", *IEEE Trans. on Power Delivery*, 26, no. 1 (2011).

[9] E. Alegria, T. Brown, E. Minear, R.H. Lasseter. "CERTS Microgrid Demonstration with Large-Scale Energy Storage and Renewable Generation", *IEEE Trans. on Smart Grid* 5, no. 2 (2014): 937-943.

[10] M. Illindala, G. Venkataramanan, "Small Signal Dynamics of Inverter Interfaced Distributed Generation in a Chain-Microgrid," *IEEE PES General Meeting*, 24-28 June 2007.

[11] Pacific Northwest National Labs. "Grid Architecture Version 2.3", DOE, Nov. 2014.

[12] J. Tong, and J. Wellinghoff, "Rooftop Parity: Solar for Everyone, Including Utilities", *Public Utilities Fortnightly*, August 2014, pp. 18-23.

[13] D. Forfia, M. Knight, and R. Melton, "The View from the Top of the Mountain. Building a Community of Practice with the GridWise Transactive Energy Framework, *IEEE Power and Energy Mag.,* April 2016, pp. 25-33.

[14] R.H. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromsom, A.S. Melipoulous, R.Yinger, J. Eto, "Integration of Distributed Energy Resources: The MicroGrid Concept", Lawrence Berkeley National Laboratory, Pub. No. LBNL-50829, 2002.

[15] J. Eto, R. Lasseter, B. Schenkman, J. Stevens, H. Volkommer, D. Klapp, E. Linton, H. Hurtado, J. Roy, N. Lewis, "CERTS Microgrid Laboratory Test Bed", California Energy Commission, Pub. No. CEC-500-03-024. 2008.

[16] E. Alegria, A. Ma, O. Idrees, "CERTS Microgrid Demonstration with Large Scale Energy Storage and Renewables at Santa Rita Jail", US Department of Energy, Pub. No: DE-FC26-08NT02872, 2014.

[17] D. Angeli, R. Amrit, and J.B. Rawlings, "On average performance and stability of economic model predictive control." *Automatic Control, IEEE Transactions on* 57.7 (2012): 1615-1626.

[18] M.L. Fisher, "The Lagrangian relaxation method for solving integer programming problems." *Management Science* 50.12_supplement (2004): 1861-1871.

[19] V.M. Zavala, "New Architectures for Hierarchical Predictive Control", *in Proceedings of DYCOPS,* 2016.

[20] V.M. Zavala, "A multiobjective optimization perspective on the stability of economic MPC", *IFAC-PapersOnLine* 48.8 (2015): 974-980.

[21] Gridwise Architecture Council. http://www.gridwiseac.org/about/transactive_energy.aspx .

[22] Gridwise Architecture Council, "Transactive Energy Framework, Version 1.0", US Dept. of Energy, Pub. No.: PNNL-22946 Ver1.0, Jan. 2015.

Robert H. Lasseter received the Ph.D. in Physics from the University of Pennsylvania, Philadelphia in 1971. He was a Consulting Engineer at General Electric until he joined the Department of Electrical and Computer Engineer at University of Wisconsin-Madison in 1980. Dr. Lasseter is internationally recognized as one of the earliest and most influential pioneers in the microgrid field. His professional career during the past 40 years has been dedicated to applying power electronics to utility systems. He is the technical lead for the Consortium for Electrical Reliability Technology Solutions' (CERTS) Microgrid Project. CERTS's microgrid architecture is widely implemented and recognized for its plug-and-play flexibility.

Thomas M. Jahns (S'73–M'79–SM'91–F'93) received S.B., S.M., and Ph.D. degrees in electrical engineering from MIT in 1974 and 1978. In 1998, he joined the Department of Electrical and Computer Engineering, University of Wisconsin-Madison, as the Grainger Professor of Power Electronics and Electric Machines, where he is currently a Co-Director of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC). Prior to joining UW, he worked at GE Corporate Research and Development, Niskayuna, NY, for 15 years. Dr. Jahns received the 2005 IEEE Nikola Tesla Technical Field Award. He is a Past President of the IEEE Power Electronics Society. Dr. Jahns was elected as a member of the US National Academy of Engineering in 2015.

Bruce C. Beihoff (M 1981, SM 2011). He graduated from the University of Wisconsin Madison/ Milwaukee with degrees in Mechanical engineering /physics. His employment experience over 38 years included General Electric, UPS, Eaton Corporation, Rockwell International, Whirlpool Technologies, and the University of Wisconsin-Madison. His special fields of interest include systems engineering and multi-physics analysis of complex systems. Mr. Beihoff holds 46 patents related to broad areas of electrical and mechanical engineering. Mr. Beihoff has been honored with innovation and engineering accomplishment awards by Eaton, Rockwell, and the University.

Gary Radloff is a researcher at the University of Wisconsin-Madison and the Director of Midwest Energy Policy Analysis for the Wisconsin Energy Institute (2009 to present). He is an Honorary Associate/Fellow with the Nelson Institute, Center for Sustainability and the Global Environment (SAGE). Radloff has also served as the Interim Director with the Wisconsin Bioenergy Initiative at the Univ. of Wisconsin. He is the lead author or co-author of the numerous reports: Policy Strategies to Catalyze the Energy Technology Innovation System in Wisconsin and the United States (2015); Transforming the Grid from the Distribution System Out (2014); to name but a few. Past activities include helping to coordinate policy initiatives such as the Governor's Consortium on the Bio-based Industry and the Working Lands Initiative.

Victor M. Zavala is the Richard H. Soit Assistant Professor in the Department of Chemical and Biological Engineering at the University of Wisconsin-Madison. Before joining UW-Madison, he was a computational mathematician in the Mathematics and Computer Science Division at Argonne National Laboratory. He holds a B.Sc. degree from Universidad Iberoamericana and a Ph.D. degree from Carnegie Mellon University, both in chemical engineering. He is currently the recipient of a Department of Energy Early Career Award under which he develops scalable optimization algorithms. He is also a technical editor of the Mathematical Programming Computation journal. His research interests are in the areas of mathematical modeling of energy systems, high-performance computing, stochastic optimization, and predictive control.