Joseph Paladino

electricity infrastructure

the application of grid architecture

THE ELECTRIC GRID HAS EXPErienced technological and institutional evolution throughout its history. However, we are currently facing a dramatic structural transformation. Five tightly interconnected forces are collectively driving grid transformation, imposing requirements for advanced functional capabilities, and ultimately shaping how utilities and regulators determine effective technology investment strategies.

- ✔ U.S. federal, state, and local policies favor the adoption of renewables and distributed energy resources (DERs) and enable greater customer choice.
- ✔ There is an increase in available technology due to cost reductions and business offerings of information management, computing, communication systems, and renewable resources and DERs.
- ✔ New participants have emerged in the management and generation of electricity and as providers of grid services, including utility customers, energy services companies, and technology merchants.
- ✔ The convergence of the electric grid with other systems, such as transportation infrastructure, poses design challenges and raises concerns regarding security and resilience.
- ✔ The reliability and resilience of the grid need to improve, including resilience in the face of potential cyber and physical attacks.

The transformation to a more distributed and networked energy system is not occurring consistently across the United States or worldwide, but it is occurring rapidly where these forces come together. Often, the rate of policy and technology advancement challenges the ability of regulators and utilities to devise well-crafted and prudent technology investment strategies that support grid modernization needs. During the second quarter of 2018, 42 U.S. states and Washington, D.C., undertook a total of 302 policy and regulatory actions related to grid modernization, compared to 36 states and 181 actions during the same period in 2017. These actions included guidance on deployments of energy storage and microgrids, investigations on integrated planning processes that include DERs, and proceedings on rate reform to accommodate the new technology and customer preferences.

Technology is advancing at a rapid pace. As we witnessed the rapid adoption of solar technology, we are now seeing the uptake of energy storage, microgrids, customer-based information platforms, cloud services, and electric vehicles. Electric-vehicle sales forecasts worldwide show a surge in sales after 2025, increasing to US$30 million or greater by 2030, up from US$1.1 million in 2017. Although the exact number of sales is difficult to predict, reducing the effective charging time of electric vehicles, through advancements currently underway in vehicle charging technology, would have a dramatic effect on sales and subsequent grid infrastructure requirements.

As a result, grid operators are exploring approaches that permit system-wide observability as we increase the number of DERs at the grid edge. These distributed resources can affect the net load curve dramatically over short time frames. Likewise, the industry wishes to understand how to best deploy the enhanced functionality of smart inverters and other controllers to better manage solar energy and other forms of distributed resources. Fundamentally, both regulators and utilities are interested in the development of rational technology implementation plans that provide prudent but necessary approaches for meeting their grid modernization needs over time.

Imagine the electric grid as an ultralarge-scale system as it becomes more decentralized and integrated with a variety of heterogeneous parts, which often have conflicting needs and objectives. Natural ecosystems and cities are examples of ultralarge-scale systems; they are not necessarily designed through top-down engineering, yet they are highly complex and organized, made possible by fundamental components and processes that enable coherent growth. Our challenge is to institute the appropriate processes and design considerations to maintain a stable, coherent, and manageable grid system as it evolves. To do so, holistic strategies for the deployment of advanced grid capabilities are needed to effectively address the increased level

(continued on p. 97)

Digital Object Identifier 10.1109/MPE.2019.2918819
Date of publication: 19 August 2019

(continued from p. 100)

of complexity and uncertainty presented by continual technological advancement, policy shifts, and changing customer expectations. Such strategies also need to consider reliability, affordability, security, and resilience as outcomes.

Over the past few years, the U.S. Department of Energy (DOE) has worked closely with several U.S. state commissions and utilities to develop approaches and design principles that could lead to the development of effective grid modernization strategies. The DOE's effort, called the *Next-Generation Distribution System Platform* (*DSPx*) initiative, has attempted to bring business and technological considerations together to help form a holistic understanding of requirements associated with grid structure and function that can then inform more detailed technology implementation plans. Working with both regulators and utilities provides a more coherent understanding of expectations as well as roles and responsibilities associated with the grid modernization process.

The first phase of the DSPx effort resulted in the development of a three-volume report that maps policy objectives to grid capabilities and functions (volume 1), examines the maturity of technology to achieve needed grid functions (volume 2), and provides decision considerations for developing and implementing grid modernization strategies (volume 3). The DOE is developing a fourth report, due in the third quarter of 2019, that will more fully describe the process for determining requirements for grid structure and function to meet policy objectives and anticipated customer expectations, the timing and sequencing of technology investments, how grid modernization planning interfaces with traditional and more integrated planning processes, and methodology for determining the cost-effectiveness of grid infrastructure choices.

A central feature of the planning framework being developed through the DSPx initiative is the application of grid architecture as a discipline to undertake the requisite structural analysis. As is discussed in more detail in this issue of *IEEE Power & Energy Magazine*, grid architecture, as applied at the Pacific Northwest National Laboratory, is primarily concerned with structure, for example, the intricate manner in which a market or industry structure relates to the cyberphysical structure and how grid structure can be designed to best support future requirements. Structural considerations must come early in the grid modernization process and deal with the vast amount of legacy structures inherited from the 20th-century grid. Applying grid architecture early and throughout

the grid modernization process can help reduce unintended consequences and lead to more rigorous approaches for problem solving. For example, grid architecture could help ensure that a robust sensing and communications platform layer can support multiple decoupled grid functions. Likewise, grid architecture is showing how to structure grids for resilience in addition to the more traditional approach of component hardening to improve grid resilience.

When grid architecture as a discipline was first introduced to the DOE in 2014, it was immediately recognized as a new and superior way to think about the entire electric power grid, not just the circuits or the controls or the information systems, and as a means to manage complex changes to the grid. The ability of grid architecture to address system complexity began to be understood by several state public utility commissions by mid-2015, but it was first recognized in a formal sense by the Hawai‘i Public Utilities Commission, which directed in January 2017 that the Hawaiian Electric Company (HECO) and its stakeholders collectively examine the application of such architectural concepts in the development of a grid modernization strategy. The HECO strategy, approved by the commission in June 2018, applies grid architecture concepts to work through design strategies needed to manage the complex set of DERs envisioned for Hawai‘i. Other U.S. state regulatory commissions and utilities have since begun to apply DSPx materials and grid architecture concepts in the development of their grid modernization plans. We have also seen the early use of this in other countries, including Australia, The Netherlands, France, the United Kingdom, and Colombia.

There are three main principles of grid architecture briefly addressed in this article: coordination, scalability, and layering. These principles are often overlooked in efforts to advance grid capabilities, yet they are essential concepts in the structural analysis leading to effective grid modernization strategies. These are discussed in more detail in this issue.

Coordination is the process that causes or enables a set of decentralized elements to cooperate to solve a common problem. The advent of mixed sets of DERs and entities other than utilities that own or manage them, such as aggregators, shifts the engineering problem from one of control to both control and coordination. An important first step is to delineate the respective roles and responsibilities of all participants in grid operations and determine their needs with respect to business objectives, market responsibilities, device or system performance constraints, and data requirements. The resulting analysis should lead to the development of sensing, communication, control, and data management schemes that permit coordination and observability under the full set of anticipated grid conditions. A carefully crafted coordination framework should address interfacing requirements across the transmission, distribution, and customer domains, including interoperability and grid code requirements. Existing (legacy) coordination frameworks often have problems, such as gaps and hidden coupling, that can become problematic at high levels of DER penetration.

Scalability is the ability of a system to accommodate an expanding number of endpoints or participants without having to undertake major rework. We can assume that each device or participant will have inherent performance capabilities and constraints as well as selfish interests, which may even change quickly over time. The ability to scale includes accommodating an increasing number of DER devices in a way that also permits optimization locally and system wide. As is discussed in greater detail in this issue, the application of laminar coordination frameworks that use a regular layered structure is one approach for addressing the scaling and optimization problem.

Layering and platform structure enable the application of fundamental or commonly needed capabilities and services to a variable set of uses or applications through well-defined interoperable interfaces. Many utility systems are arranged in siloes, each vertically structured with its own sensors and networks and coupled through back-end data connectors. Siloes present significant system integration challenges and make it difficult to easily add applications and functions. Even worse, siloes may allow for a failure in one application silo to cascade through to the others, a situation that is fundamentally antiresilient. Grid architecture shows how to layer core system components into a platform to serve multiple applications. These core components, such as information management, sensing, and communications systems with the physical grid, can then serve as a platform to enable the full set of envisioned grid functions, including those required for convergence with other infrastructure. The importance of the platform concept is becoming widely recognized across the industry, including by the Public Utilities Commission of Ohio (PUCO) in their PowerForward Roadmap initiative. As stated by PUCO Commissioner, Vice-Chair M. Beth Trumbold:

> U.S. DOE guidance on how to tackle the complexities of a modern distribution grid in Ohio has been instrumental in our PowerForward Roadmap. The PUCO envisions the grid as a secure and open platform that allows other technologies and applications to interface with it seamlessly; the hard part is how to get there. Our intention is to focus on the fundamentals of grid architecture, a structural framework and process, and to work through these complex issues in a logical way.

Ultimately, a determination of structural and functional requirements needed to address policy and timing objectives should be conducted early and throughout a grid modernization effort. Grid architecture provides a disciplined approach to consider the set of structural requirements fundamental to a holistic planning process. Robust grid modernization strategies based on the application of these principles can then help set the logic for technology selection and sequencing in grid modernization implementation plans.