Agile Fractal Systems: Re-Envisioning Power System Architecture

Tim Heidel & Craig Miller
National Rural Electric Cooperative Association (NRECA)

Rapidly falling costs of distributed electricity generation such as solar photovoltaics and storage technologies coupled with the growing emphasis on improving electric power system resiliency have motivated the investigation of alternative architectures for planning and operating electric power systems. The methods that have been used to plan and operate the grid since the dawn of electrification have worked well. Indeed, the U.S. grid has set the absolute standard for scale and performance of engineered systems for more than a century, but new technologies, economics, social attitudes, and environmental sensibilities are calling this model into question.

Recent advances in power electronics, computation, and communication technologies could provide the opportunity to optimize and control grid operations closer to the locations where power is ultimately consumed (Kassakian et al. 2011). This could offer significant efficiency, cost, reliability, and emissions benefits. However, the methods that have been relied on for designing and operating power systems historically will prevent the full realization of the potential benefits associated with these technologies. Power system design and control methodologies that are both “agile” and “fractal” will be needed to full realize the benefits offered by distributed generation and storage technologies.

BACKGROUND AND MOTIVATION

In 2014, then U.S. Secretary of Energy, Dr. Ernest Moniz in a speech to the IEEE defined the electrical grid of North America as “a continent spanning machine of immense complexity that is at its best when it is invisible.” (Moniz 2014) There has probably never been a more succinct and accurate definition of the grid we have built since the first central power plant opened in 1892 in Manhattan. The electric power delivery system has evolved continuously since the dawn of electrification in the late nineteenth century. Generations of engineers have identified improvements that enabled greater reliability, resilience, and lower cost. Over time, every component and procedure has been relentlessly refined and polished. Today, the grid operates with impressive reliability often making it invisible. The reliability routinely achieved today is largely a consequence of the system’s scale, literally its angular momentum. Titanic power flows from the Hoover Dam and its kin, an immense fleet of large-scale central power generation stations throughout the country. Small generators and loads are effortlessly swept into synchronicity by the current flowing from these huge turbines. This has proven to be a very good way to design a system, especially given the economies of scale and increased efficiency of most electricity generation technologies. However, the recent, rapid growth of distributed energy resources located at the far, thin edge of the grid is calling this model in question. As these resources continue to proliferate, individual homes, businesses, and factories will begin to have a far larger influence on the operation of the grid both locally and throughout the system (Kristov 2015).

Distributed and, particularly, customer-owned generation, thermal and electrical storage and load control technology such as communicating thermostats or building management systems raise the question of what constitutes a grid. Is the grid the continent spanning totality, or is it one utility, one feeder, one lateral, or one building? The answer is, increasingly, all of these. A building energy management system may control rooftop PV or gas powered combined heat and power technologies, loads, energy storage, purchases from or sales to the grid. It is an electrical grid in every sense of the word except scale and presents many of the same problems in optimal control. In running the building well, it must also act in harmony with all the other actors in the grid. This will become increasingly critical as the electric power system as a whole evolves to rely ever more heavily on distributed energy resources.

We are in a unique time, when we are being challenged to adapt that grid for new and changing needs and offered the opportunity to think beyond incremental improvement to a fundamental reimagining and reinvention, building on emergent technology in distributed generation and sensor technology and advances in communications and industrial controls.

AGILE AND FRACTAL GRIDS

A useful definition for a grid is "a collection of electrical assets (generation, load, storage, transport) than can be controlled by a single entity." By this definition, grids range from individual buildings to Regional Transmission Organizations (RTOs) spanning multiple states. This hierarchical model of the grid challenges the old simplifying dichotomy in which generation and transmissions companies thought of the distribution system as an exogenous, slowly varying, uncontrollable load and distribution companies treated the transmission systems as an infinite bus. With many systems and actors involved, the fundamental problem in operations moves from pure control to "harmonization."

We believe that this harmonization must be agile and fractal. To be "agile" in this context, a grid must be capable of dynamically reconfiguring and optimizing based on rapidly changing local conditions. Even under ideal conditions the grid is constantly changing – components are installed and retired every day, and load varies with weather, season, and the vagaries of human activity. Beyond this "blue sky" variation, local storms, natural disasters, equipment failures, and other factors disrupt "normal" grid operations. These variations have always been present. However, they are poised to become more pronounced as new weather-dependent generation sources (such as solar and wind) and new electricity uses (such as electric vehicles) become ubiquitous. As we build the grid of the future, we must think not of static design and build, but of a design process that never ends, that is constantly evolving and which allows us to routinely adapt operation on a continuous basis to account for changing conditions and circumstances. As the new technologies allow us to build a more efficient grid, the fiction of a static grid – designed to a fixed point and then operated as designed – will be further undermined. A campus or individual building in an office park may sometimes operate autonomously, sometimes focusing on local coordination, sometimes as part of a much larger whole. We must think of the future grid as a grid of grids of grids, dynamically adapting when challenged.

"Fractal" design is an essential element to achieve the desired agility. Taking inspiration from fractal geometric figures, fractal grids will exhibit the same control and operational characteristics at every scale. If we have distinct and incompatible methods of operating buildings, campuses, feeders, distribution systems, generation and transmission systems, RTOs and Independent System Operators (ISOs), we will not achieve the high potential agility and we will be locked into a morass of interoperability standards and local, ad hoc, and idiosyncratic methods of coordination. If we move, instead, to finding commonality in the problems of grid operations across scale, we can move closer to a grid that can be continuously adapting, collaborating, and harmonizing to achieve greater reliability, resiliency, and efficiency. In a fractal grid, any part of the overall power system will be capable of performing all of the functions of the full grid today. With fractal design, parts of the grid could safely isolate from the rest of the power system if and when it was optimal to do so (due to local weather conditions, fuel costs, etc.) but join back into the broader system when conditions change. Decisions on how and when to segment parts of the system will be based on economic, engineering, and business considerations.

Figure 1 illustrates the concept of an agile, fractal grid. In Figure 1a, a distribution grid operates similar to how one might operate today. Energy flows to customers from two different substations and the system is operated with a tree structure. A normally open switch isolates the green and blue portions of the distribution system. Individual customers with generation or storage can use power generated locally and may in some circumstances be able to feed that power back onto the local grid. Figure 1b illustrates how the grid might be reconfigured after an equipment or line failure. In this scenario, energy is still fed from two substations, but certain customers are now receiving power from Substation B instead of Substation A. This scenario is already becoming increasingly common as utilities install automated switching technologies into distribution systems. Finally, Figure 1c illustrates the potential for a portion of the grid, corresponding to a small collection of customers to further isolate from the rest of the system for business or economic reasons. That portion of the system consumes power, in this specific scenario, purely based on locally available generation resources. Eventually, one would generally expect the operation of the system to return to that illustrated in Figure 1a.

TECHNICAL CHALLENGES

Re-architecting the control of electric power systems entirely will not be achieved quickly or simply. Indeed, the explicit study of grid architecture is emerging as an important new research domain (Taft and Becker-Dippmann 2015). However, the technology needed is there or nearly there. Achieving a plausible transition from current state-of-the-art to an agile and fractal future will rely primarily on three classes of innovation: (1) Precise state awareness, (2) Precise controls, and (3) Advanced analytics (including forecasting and optimization technologies).

First, successful grid operations in an agile, fractal environment will require precise knowledge of the state of the grid at all times and locations. Grid operators need to understand the operating state and the real-time capability of loads, generators, and storage devices. Ensuring the safety of utility personnel and customers will also require a precise understanding, at all times, of what parts of the system are connected to each other (and what reconfiguration options are permitted). Fortunately, recent years have seen dramatic advances in sensor technologies that can contribute to state awareness, such as communicating digital consumption meters and distribution system phasor measurement units (von Meier et al. 2017). The rapidly falling costs of communications technologies also enables grid operators at all levels to communicate state related information more often and on a more granular basis.

Achieving agile, fractal grids will also require more precise controls. Many companies are developing advanced switching and power electronics technologies that can enable more rapid and precise control (Bhattacharya S. 2017). More advanced protection system devices, reactive power controllers, networked switches, and disconnect-capable meters can enable more agile Volt/VAR control throughout the system and a wider range of feasible system reconfiguration options. Many of these technologies are already gaining adoption in the utility community today to reduce system losses, gain greater efficiency through conservation voltage reduction, or to enhance resiliency during and after storms. The power electronics-based inverters that interface distributed energy resources such as photovoltaics or storage devices will play an increasingly important role in enabling more precise control of the system.

Finally, a new generation of electricity system data analytics will be required (National Academies 2016). More precise and accurate algorithms for forecasting the evolution of customer needs and generation resource capabilities will be required. Scalable algorithms will also need to be developed for optimizing large, diverse fleets of controllable resources (Panciatici et al. 2014). These algorithms will help translate improved state awareness into decisions on how to best deploy distributed energy resources and other controllable devices. Effectively and securely managing the transport, storage, analysis, of data among a large number of diverse stakeholders will be a key architectural design challenge. Advances in the analysis of corrupted or incomplete data will also be critically important. Many of these advances will rely on techniques for making decisions subject to significant uncertainty.

CONCLUSION

Declining costs of renewable and distributed generation technologies, higher performance computing, and high-bandwidth communications coupled with advances in power electronics and related control technologies, are making analytically driven and agile control of the grid technologically possible. Indeed, many of the individual components required to realize agile, fractal grid operations are either already available or in advanced development. Nonetheless, significant research and development is still needed on how to optimally integrate all of required component technologies together. A particular challenge will be harmonizing this vision for how the grid will operate in the future with the reality of continuous incremental change which is necessary when engineering all critical infrastructure technologies. Control systems that are consistent with agile, fractal operation will have to coexist for some time with the control approaches that are used widely today. Ultimately, as this new architecture for the control of electricity delivery infrastructure becomes widely used, we expect it will be possible to achieve greater reliability, resiliency, and efficiency while also easing the challenge of adapting to future changes. Finally, we believe insights gained throughout this transformation could have important implications on the design of other highly distributed engineered systems.

REFERENCES

Bhattacharya S. 2017. Smart Transformers Will Make the Grid Cleaner and More Flexible. IEEE Spectrum, June 2017. Available: http://spectrum.ieee.org/energy/renewables/smart-transformers-will-make-the-grid-cleaner-and-more-flexible.

Kassakian JG, Schmalensee R, Desgroseilliers G, Heidel TD, Afridi K, Farid AM, Grochow JM, Hogan WW, Jacoby HD, Kirtley JL, Michaels HG, Perez-Arriaga I, Perreault DJ, Rose NL, Wilson GL. 2011. The Future of the Electric Grid: An Interdisciplinary MIT Study. Massachusetts Institute of Technology, MIT Energy Initiative, December 2011 Available: http://mit.edu/mitei/research/studies/the-electric-grid-2011.shtml.

Kristov L. 2015. The Future History of Tomorrow's Energy Network. Fortnightly Magazine, May 2015.

Moniz E. 2014. Keynote Address, IEEE Innovative Smart Grid Technologies Conference, February 19, 2014, Washington, DC.

National Academies of Sciences, Engineering, and Medicine. 2016. Analytic Research Foundations for the Next-Generation Electric Grid. Washington, DC: The National Academies Press. https://doi.org/10.17226/21919.

Panciatici P, Campi MC, Garatti S, Low SH, Molzahn DK, Sun AX, Wehenkel L. 2014. Advanced optimization methods for power systems. Proceedings of the 18th Power System Computation Conference, August 2014, Wroclaw. doi: 10.1109/PSCC.2014.7038504.

Taft JD, A Becker-Dippmann A. 2015. Grid Architecture. Pacific Northwest National Laboratory, January 2015, Richland, Washington. Available: http://gridarchitecture.pnnl.gov/media/white-papers/Grid%20Architecture%20%20-%20DOE%20QER.pdf

von Meier A, Stewart E, McEachern A, Andersen M, Mehrmanesh L. 2017. Precision Micro-Synchrophasors for Distribution Systems: A Summary of Applications. IEEE Transactions on Smart Grid, June 2017, doi: 10.1109/TSG.2017.2720543

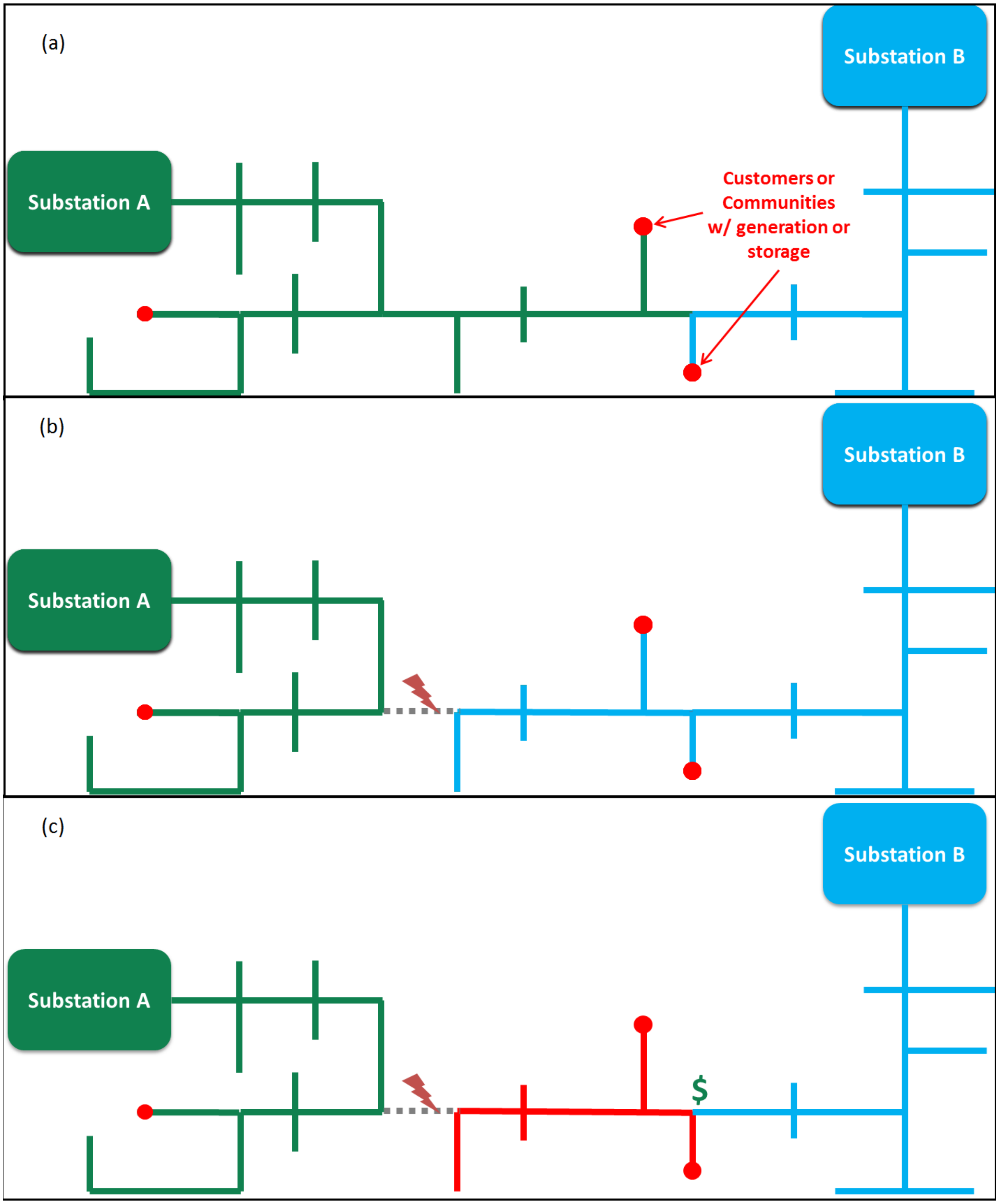

Figure 1: Agile, Fractal Grid Scenarios