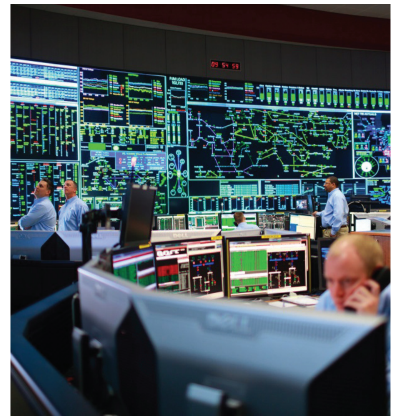
# Analytic Research Foundations for the Next-Generation Electric Grid



*Power system tools in use in the PJM control center. Source: PJM*

Electricity is the lifeblood of modern society, and the vast majority of people rely on obtaining electricity from large, interconnected power grids. However, the grid that was developed in the 20th century is no longer adequate to meet the needs of the 21st century. The next-generation electric grid must be flexible enough to accommodate intermittent renewable energy sources such as wind and solar, and it must be resilient enough to withstand disturbances caused by attacks or disasters. Precisely tailoring the performance of this next-generation electric grid will require the collection and effective analysis of real-time, large-scale data from across the system. Designing, monitoring, and controlling this "smart grid" will require advanced mathematical capabilities to ensure optimal operation and robustness. While present-day mathematical models can predict the behavior and interaction of hundreds of thousands of components—a capability that is needed daily to match power generation to demand and to keep utility-scale operations profitable—these models break down for larger, more complex systems. At the request of the Department of Energy (DOE), this report provides guidance on the long-term critical research areas in the mathematical sciences that should be given priority in order to advance the analytic foundations needed to make the next-generation electric grid a reality. The report advises DOE to increase research in mathematical optimization and in dynamical system theory in order to more accurately model the next generation grid. It recommends improving data availability and usage through the creation of synthetic data and the development of open-source software. It also recommends that DOE broaden its coordination of research in its National Laboratories to include academic and industrial researchers and that it establish a National Electric Power Systems Research Center.

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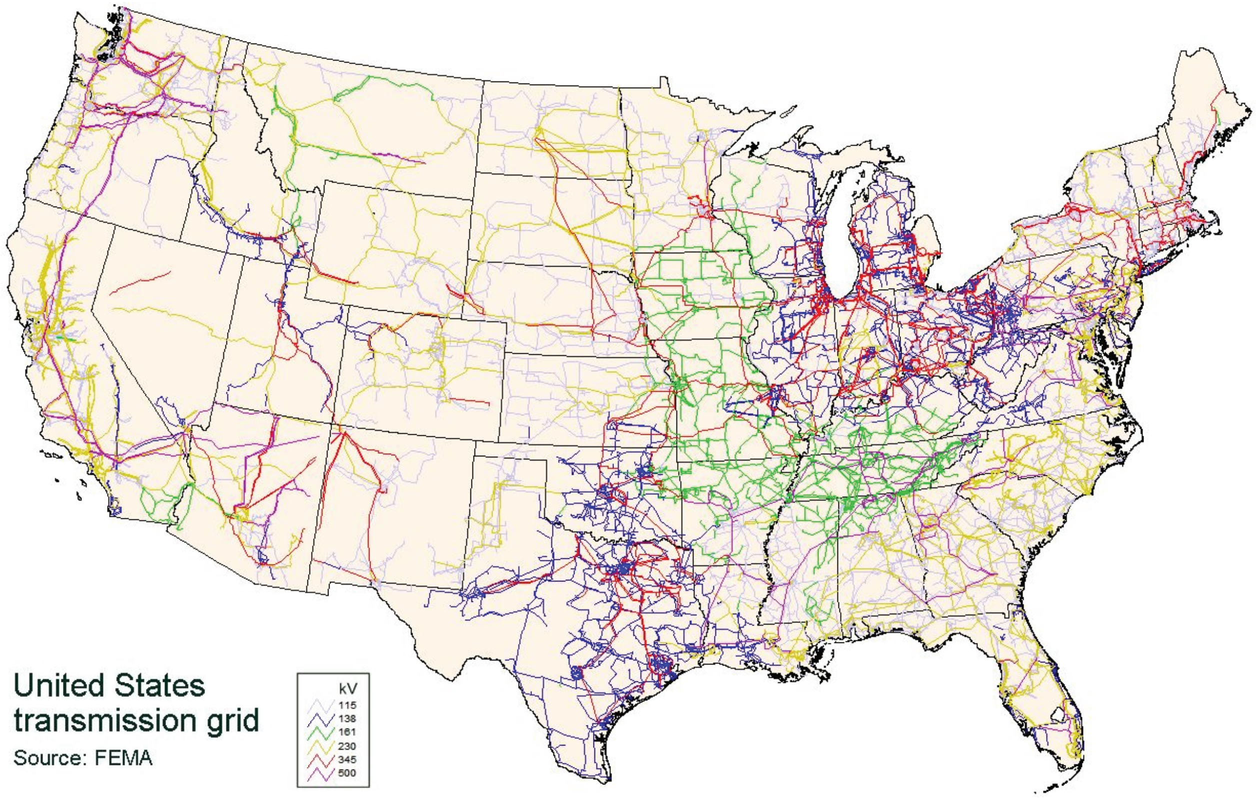
## BACKGROUND

Most of North America is powered by four electricity interconnections, linked systems of power generators and electrical loads that provide electricity to consumers distributed over thousands of square miles. Large-scale interconnects have two significant advantages. The first is reliability. By interconnecting hundreds or thousands of large generators in a network of high-voltage transmission lines, the failure of a single generator or transmission line is usually inconsequential. The second is economic. By being part of an interconnected grid, electric utilities can take advantage of variations in the electric load levels and differing generation costs to buy and sell electricity across the interconnect. This provides an oppor-




tunity to operate the transmission grid efficiently. However, large interconnects also have the undesirable side effect that problems in one part of the grid can rapidly propagate across a wide region if the system becomes overwhelmed, resulting in the potential for large-scale blackouts such as occurred in the Eastern Interconnect on August 14, 2003. Therefore, there is a need to optimally plan and operate what amounts to a giant electric circuit so as to maximize the benefits while minimizing the risks.

Mathematical modeling and control of the electric grid has been an active area of research for decades. However, in 1996 a major outage that affected 11 Western states and 2 Canadian provinces—coupled with emerging concerns about the Y2K problem—made it clear that we lack a complete understanding of the overall system and its frailties. For several decades the Electric Power Research Institute funded research that was largely mathematical in nature to develop tools for recognizing early signs of instability and means to counter them. More recently, the DOE has been supporting research to develop the analytical and computational tools that will be necessary for the next-generation grid. This report provides recommendations to the DOE in four categories: data availability, modeling capabilities, improved algorithms, and organizational structure.

## IMPROVING ALGORITHMS FOR LARGE-SCALE USE

The future grid will rely on integrating advanced computation and massive data to better support decision making. If the number of nodes increases and the time-scale for decision making shortens as expected in the future grid, current mathematical algorithms will not be sufficient to make the transition, even if they are implemented on more powerful computers. Instead, the future will require new classes of models and algorithms. Optimal power flow models, which determine how a change in power generation or consumer demand would affect the flow of electricity throughout the system, are of particular importance. These models are critical for ensuring there is sufficient power generation available to match the forecast electric load, and they are also used to calculate energy pricing in the electricity market.

**RECOMMENDATION:** DOE should develop and test a full ac optimal power flow (ACOPF) model with an optimization algorithm using all nodes in the market area, taking advantage of supercomputers and parallel processing, and respecting all thermal and voltage constraints.

## MAKING DATA AVAILABLE TO THE LARGER RESEARCH COMMUNITY

One current impediment to research is that some of the formats used by utilities to exchange power flow data are proprietary and not fully available to the public, which limits outsiders from using that data for research purposes. Because specialized software is needed to access the data, power engineers and others in the larger research community have difficulty developing and testing their models and algorithms.

**RECOMMENDATION:** The Federal Energy Regulatory Energy Commission (FERC) should require that all text file formats used for the exchange of FERC715 power flow cases be fully publicly available.

**RECOMMENDATION:** FERC should require that descriptions of all models used in system-wide transient stability studies be fully public, including descriptions of any associated text file formats.

## CREATING SYNTHETIC DATA LIBRARIES

It is clear that the availability of realistic data is critical to enabling the power engineering community to make verifiable scientific assessments. However, much of the data being generated by the electric power industry is viewed as proprietary, both because it would reveal information about company operations and because it might reveal information useful to terrorists. Synthetic data created to sufficiently mirror real grid operations would allow researchers to test tools and techniques while minimizing these risks.

**RECOMMENDATION:** Given the critical infrastructure nature of the electric grid and the critical need for developing advanced mathematical and computational tools and techniques that rely on realistic data for testing and validating those tools and techniques, the power research community, with government and industry support, should vigorously address ways to create, validate, and adopt synthetic data and make them freely available to the broader research community.

**RECOMMENDATION:** DOE should sponsor additional efforts to create synthetic data libraries to facilitate studies of, and tool-building for, the reliability and control of the future electric grid.

## APPLYING DATA-DRIVEN ANALYTICS TO POWER INDUSTRY OPERATIONS

The amount of data being collected about the power system from sensors, smart meters, and even social media has been growing at a staggering rate. However, for reasons that are not completely clear, the power industry is not making sufficient use of this available data. One explanation is that the power industry hires very few data scientists and may not fully recognize the potential value of this data for both prediction and control.

**RECOMMENDATION:** DOE should support research on data-driven approaches applied to the operations, planning and maintenance of power systems. This would include better machine-learning models for reliability, comprehensible classification and regression, low-dimensional projections, visualization tools, clustering, and data assimilation. A partial goal of this research would be to quantify the value of the associated data.

## STRENGTHENING FUNDAMENTAL AND APPLIED RESEARCH

There are many computational and engineering challenges associated with controlling and optimizing the electric grid, and nearly all of these problems would benefit from new tools in the mathematical sciences. Dynamical systems theory, a field of mathematics that studies the behavior of continuously changing systems, provides a conceptual framework for understanding the time-dependent behavior of the grid. While the prospect of developing software that integrates many types of models into a system the size of the power grid is daunting, smaller models may yield important insights that can be further tested.

**RECOMMENDATION:** DOE should support research to extend dynamical systems theory and associated numerical methods to encompass classes of systems that include electric grids. In addition to simulation of realistic grid models, one goal of this research should be to identify problems that exemplify in their simplest forms the mathematical issues encountered in simulating nonlinear, discontinuous, and stochastic time-dependent dynamics of the power system. The problems should be implemented in computer models and archived in a freely available database, accompanied by thorough documentation written for both mathematicians and engineers. Large grid-sized problems that exemplify the difficulty in scaling the methods should be presented as well.

In addition to dynamical systems, continued research in mathematical programming, a field of mathematics that is used to determine the optimal performance of complex systems, will help to further develop the capabilities needed to improve the performance of the grid.

**RECOMMENDATION:** Orders-of-magnitude improvement in nonlinear, nonconvex optimization algorithms are needed to enable their use in wholesale electricity market analysis and design for solving the ACOPF problem. Such algorithms are essential to determine voltage magnitudes. Therefore the DOE should provide enhanced support for fundamental research on nonlinear, nonconvex optimization algorithms.

The electric grid is highly complex and defies precise analysis. For that reason, the use of various kinds of machine learning, along with improved control and optimization algorithms, is important.

**RECOMMENDATION:** Integration of theory and computational methods from machine learning, dynamical systems, and control theory should be a high priority research area.

DOE should support such research, encouraging the use of real and synthetic phasor measurement unit data to facilitate applications to the power grid. Establishment of test-beds for physical experiments would provide valuable additional sources of data.

## PROVIDING OPEN-SOURCE SOFTWARE TO ASSIST RESEARCHERS

The electric generation research community would benefit from the availability of new open-source simulation software that could be used to study the behavior of the grid under varying conditions and loads. Because most of the currently available simulation tools are proprietary commercial products, it is often not possible for researchers to experiment with the models packaged with these programs.

**RECOMMENDATION:** DOE and NSF should sponsor the development of new open-source software for the next-generation electric grid research community.

## IMPROVING COORDINATION ACROSS GOVERNMENT, UNIVERSITIES, AND INDUSTRY

While the DOE has an on-going effort to coordinate the power grid research that it funds at its National Laboratories, there is a need for coordination among a broader community that includes university and industry researchers as well. Supporting research beyond the DOE National Laboratories will enable experts from fields other than power engineering to join the research effort.

**RECOMMENDATION:** DOE efforts to coordinate power grid research in its National Laboratories are important, and it should broaden this coordination to include academic and industry researchers.

**RECOMMENDATION:** The DOE should establish a National Electric Power Systems Research Center to address fundamental research challenges associated with analysis for the future electric system. The center would act as an interface between the power industry, government, and universities in developing new computational and mathematical solutions for data and modeling issues and in sharing valuable data.

The proposed center should foster a cross-disciplinary, multi-institutional approach to the analytical problems of the next-generation grid on a scale not normally possible in individual institutions. Through its industry connections, the center could help researchers understand the behavior of the current U.S. power system, contribute to its orderly evolution, and enhance and extend the capabilities of the university and broader industry communities.

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