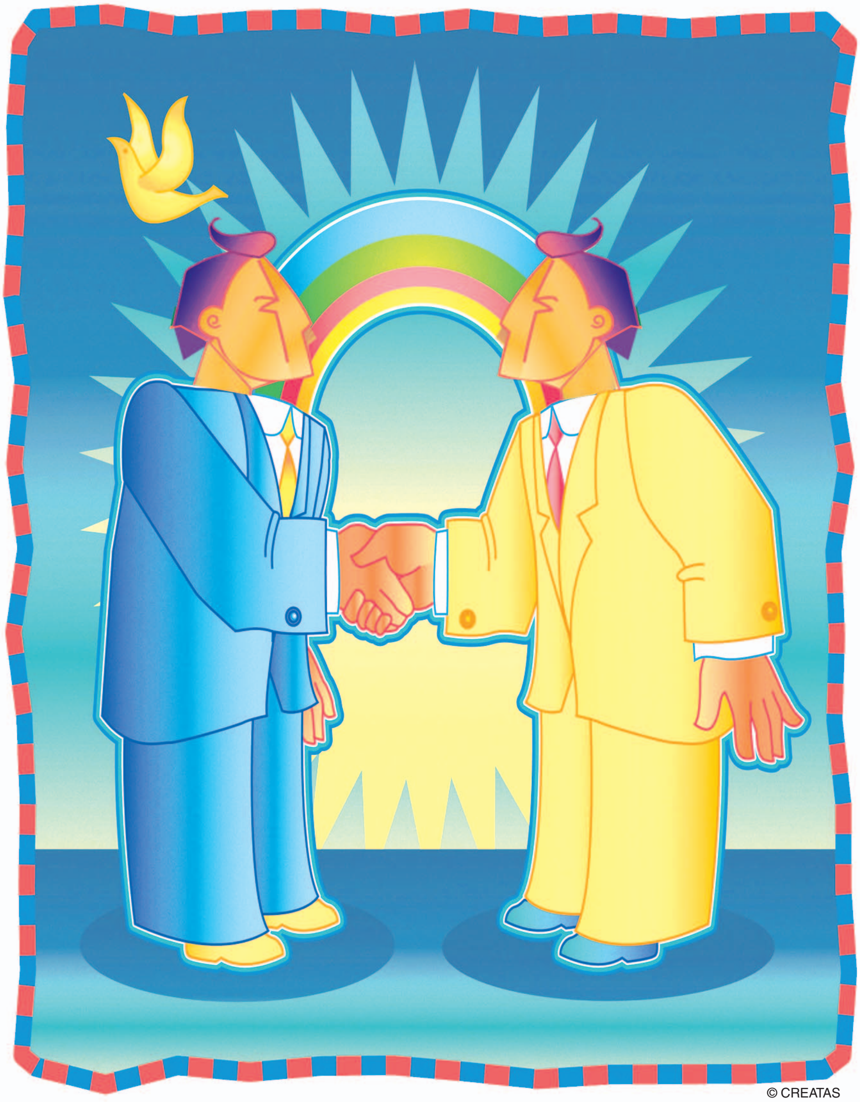
Is Teamwork the Smart Solution?

by Mladen Kezunovic, Gerald T. Heydt, Christopher DeMarco, and Timothy Mount

How One University Consortium Is Tackling Smart-Grid Research



© CREATAS

ONE OF THE MOST FORMIDABLE tasks facing humanity at the moment is how to solve the problems associated with energy supply and utilization. The issues are complex, to be sure, and they're compounded by seemingly conflicting objectives involving cost, sustainability, reliability, environmental soundness, free markets, and an energy supply that is accessible to all—anytime. Because there's special interest in enhancing the sustainability of a modern lifestyle, one approach to the problem is to use renewable resources—mainly solar and wind—to power the world economy. Some renewable resources have the

Digital Object Identifier 10.1109/MPE.2008.931384

1540-7977/09/$25.00©2009 IEEE

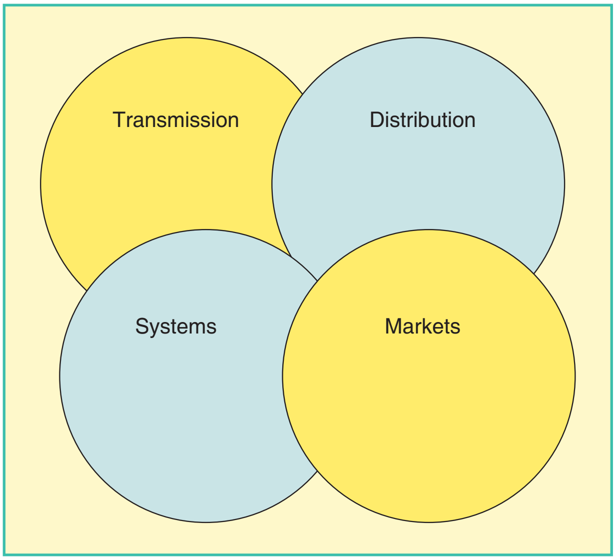


figure 1. The main contemporary focus areas of power engineering.

added benefit of low environmental impact, especially in greenhouse gas production. There's also great interest in restructured energy and power markets that are called "free" or "liberalized" in some parts of the world and "deregulated" in the United States. The deregulation of the electric power industry in many venues has resulted in a new science and engineering of power marketing. There are complex basic challenges in solving the problems that are related to an unfettered power market that results in an environmentally sound production of electric power and also a reliable and low-cost solution.

There is a distinct role for universities worldwide: to address such problems and their solutions through basic research. The nature of "basic research" often involves the formulation, development, and application of mathematical, physical, and other scientific knowledge, tailored to given challenges in a given field. In recent years, there has been considerable focus on the concept of a "smart grid" to address these challenges in energy and power engineering. The smart grid concept is not universally defined, but it is clear that the general concept requires a multipronged research and engineering effort. One way to approach basic research and the smart grid is through a university consortium—a collaborative effort among many universities that utilizes industry and scientific inputs to tackle the grand challenges of power engineering. A collaborating consortium allows for the utilization of the most qualified research expertise from several universities to solve power engineering problems. The Power Systems Engineering Research Center (PSERC), which was formed by the National Science Foundation and the collaboration of a group of 13 universities and about 40 industry sponsors, has undertaken a number of research directions.

The University Consortium's Research Focus

The challenges in power engineering and the design of a smart grid might be classified into four areas as shown in Figure 1. There is a background component to the research fields that is not depicted in Figure 1: the education and training of human resources to work on developing and deploying smart grid solutions in the future. This component works well with the concept of a university research consortium. Power engineering as a lifetime career that is attractive to students who want to solve the most complex problems, use advanced technologies in their work, and address problems that are pressing to society in general. The consortium engages graduate and undergraduate students in research and interaction with industry, two important ingredients of successful career development.

Research Challenges in Transmission Engineering

Transmission engineering has traditionally focused on overhead and underground high-voltage conductors. Protective relaying and instrumentation complements this technical venue. In the deregulated power engineering environment, many issues related to extracting the maximum benefit from all transmission assets have been researched. Some of the projects recently completed by PSERC university researchers are listed in Table 1. Many more reports may be found on the PSERC Web site: http://www.pserc.org/.

Research in the area of transmission engineering needs to cover many issues across different disciplines, including power engineering, computer engineering, communications, materials, and chemical engineering. Researchers at the schools

table 1. Sampling of research challenges in transmission engineering recently addressed by PSERC researchers.

Project Title	Project Status
Enhanced Reliability of Power System Operation Using Advanced Algorithms and IEDs for On-Line Monitoring: Part I, Part II	Completed 2005
Performance Assessment of Advanced Digital Measurement and Protection Systems: Part I, Part II	Completed 2006
Automated Integration of Condition Monitoring with an Optimized Maintenance Scheduler for Circuit Breakers and Power Transformers	Completed 2006
Digital Protection System Using Optical Instrument Transformers and Digital Relays Interconnected by an IEC 61850-9.2 Digital Process Bus	Completed 2008
Integration of Substation IED Information into EMS Functionality	Completed 2008
Transient Testing of Protective Relays: Study of Benefits and Methodology	Completed 2008

with strong power engineering programs focused on the ways different engineering disciplines and related sciences could be applied to improve the everyday operation of power systems. The frontiers of transmission engineering are defined by a strong emphasis on improving monitoring and protection, enhancing transmission capability, and optimizing asset management.

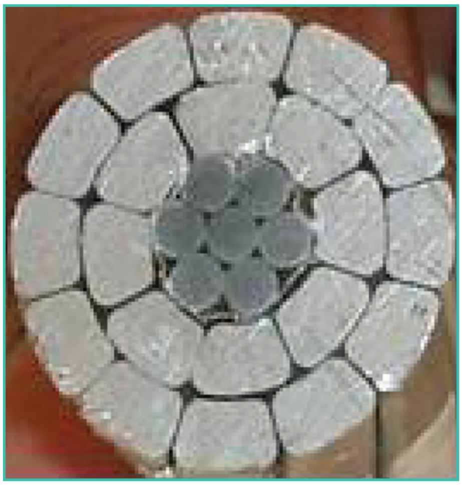


figure 2. Aluminum conductor composite reinforced (ACCR) sample evaluated for use as a high-temperature, low-sag overhead transmission conductor.

figure 3. Aluminum conductor composite core (ACCC) sample.

Improving monitoring and protection invariably includes designing new and improved sensors. Major emphasis is placed on the development and applications of optical instrument transformers as well as other optics-based sensing. This leads to interest in an all-digital substation design in which new intelligent electronic devices (IEDs) are interconnected in complex systems for processing and communicating field data. Prominent is the use of wireless and optical waveguide communications for interstation and intrastation communications. The new sensors, as well as the data integration and sharing in substations, lead to enhanced monitoring capabilities for substations, transmission lines, and the overall system. As a result, new approaches to substation state estimation, transmission line fault location, and conductor and insulator monitoring have been addressed. The availability of the waste range of substation data has led to the rapid development of condition-based maintenance approaches and techniques. This allows for the development of new optimized maintenance strategies that span from traditional reliability-centered strategies to more risk-based maintenance strategies. Also, major attention has been paid to the use of the global positioning system (GPS) of satellites, utilizing both the temporal (time reference) and spatial (geographic coordinates) capabilities for improved monitoring. The GPS-enabled intelligent electronic devices placed in substations and on transmission line towers allow new ways of monitoring system dynamic conditions and conductor sags, respectively. In a related area, the properties of high-temperature, low-sag overhead transmission conductors have been studied extensively. Figure 2 shows an aluminum conductor composite reinforced (ACCR) sample that was evaluated and Figure 3 shows an aluminum conductor composite core (ACCC) sample. Figures 4 and 5 show the microscopic details of certain high-temperature, low-sag conductor samples. Monitoring transmission lines and substations with more precise time-scale recording that produces samples measured down to milliseconds and microseconds has become available, and many researchers are looking into the benefits

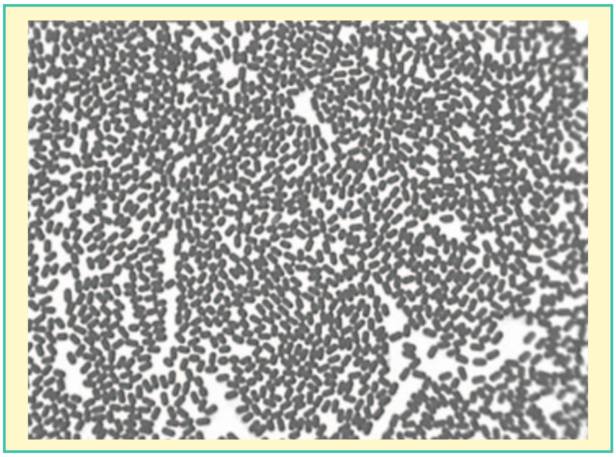


figure 4. Submicron-size Al2O3 fibers in aluminum metal matrix. This material is used in overhead transmission conductors.

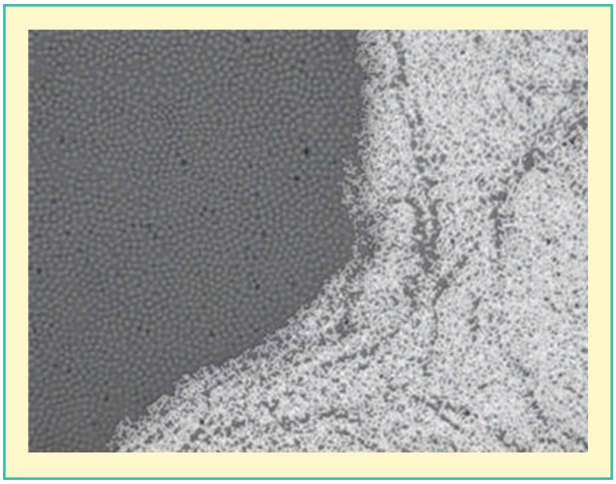


figure 5. Glass fibers and carbon fibers in epoxy resin matrix in a carbon composite used in overhead transmission.

of this field-recorded data "explosion." Major developments are focused on new relaying and monitoring capabilities using synchronized sampling and synchronized phasors. Last but not least, due to several devastating blackouts that have been occurring around the globe because of extreme loading levels in the restructured utility industry, special emphasis has been placed on improving the dependability and security of protective relays and related schemes. As a result, research has covered new test methodologies for evaluating relay performance under system conditions not traditionally encountered in relaying studies: multiple contingencies resulting in simultaneous changes in system frequency, voltage, and current during out-of-step and high-loading conditions.

An example of the research challenge in transmission engineering is to increase the efficiency of the utility personnel responsible for analyzing the faults, repairing damaged equipment, and restoring the system by utilizing substation field data integration. Nowadays, IEDs, such as digital protective relays (DPRs), digital fault recorders (DFRs), and circuit breaker monitors (CBMs) may be installed in a substation. Those devices are capable of recording a huge amount of data. The existing use of IED data is not automated. Data integration for analysis purposes in the case when IEDs from several different vendors are utilized is not straightforward due to multiple interoperability inconsistencies. The concept of data integration and information extraction is shown in Figure 6. The IEDs marked in orange may be integrated and then merged with data from other IEDs, such as sequence of event recorders (SERs), programmable logic controllers (PLCs), power quality meters (PQMs), and remote terminal units (RTUs) of a supervisory control and data acquisition (SCADA) system, to improve the analysis of faults and switching sequences. Figure 7 shows the substation data integration system architecture of an automated engineering analysis (AEA) system developed based on the integration of DFR, DPR, and CBM data in the course of recent research.

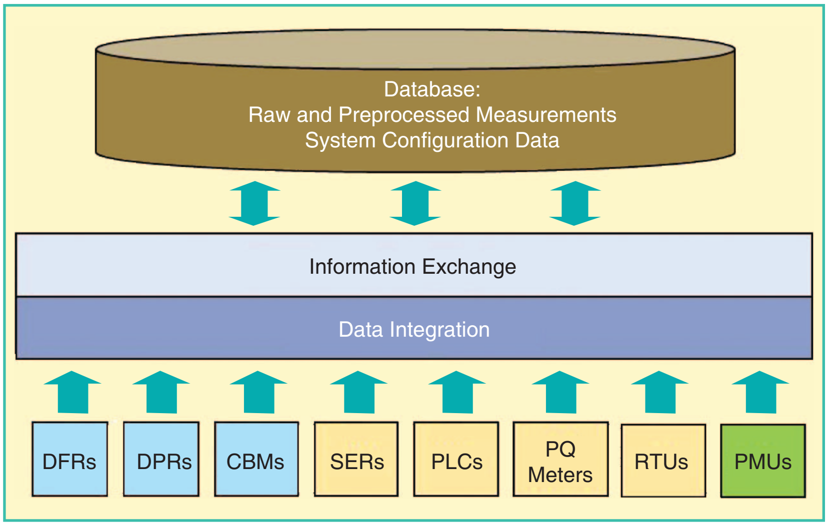


figure 6. Automated data integration and information extraction for improved fault analysis.

The system performs IED data collection automatically, converts data from all devices into a single data format, and stores that data in a database. An example of the automated collection of data in the switchyard and communication to the substation control house using wireless communications is shown in Figure 8. To enable the merging of data and its alignment across different IEDs, time synchronization and time stamping at the recording location is implemented as shown in Figure 9. The analysis applications—digital protective relay analysis (DPRA), digital fault recorder assistant (DFRA), and circuit breaker monitor analysis (CBMA)—generate reports per IED type and comprehensive reports intended for different utility groups, such as operations, protection, and maintenance, as shown in Figure 10. The protection group can be informed immediately about the fault that occurred and can make decisions concerning what action should be taken in a very short period of time. The maintenance personnel also can be informed about the status of the equipment, and any maintenance actions may be initiated very quickly. The operations group can have a much more precise view of the unfolding events, leading to increased situational awareness. The module "Preprocessing for Control Center Interface" translates nonoperational data coming from various protective relays, recorders, and monitors into information that may be merged with SCADA data and utilized by a variety of applications at the control center level. The control center staff can get additional information from IEDs that can improve the interpretation of alarms and system restoration procedures.

Research Challenges in Distribution Engineering

Distribution engineering has traditionally been that branch of power engineering that relates to the transport of energy from bulk energy systems to the point of end use. While this division may be somewhat artificial, power engineers compartmentalize solutions and research to tackle the most complex problems according to the objectives. The objectives of distribution engineering relate closely to points of end use and to the efficient use of system assets that are sized for end-use tasks. Some of the main challenges in distribution engineering and a sampling of the completed research reports by PSERC university researchers are listed in Table 2.

As an example of the kind of challenge and research that can be done, note the subject of prioritizing maintenance of underground cables. Distribution companies serving urban areas are increasingly using underground cables for distributing power

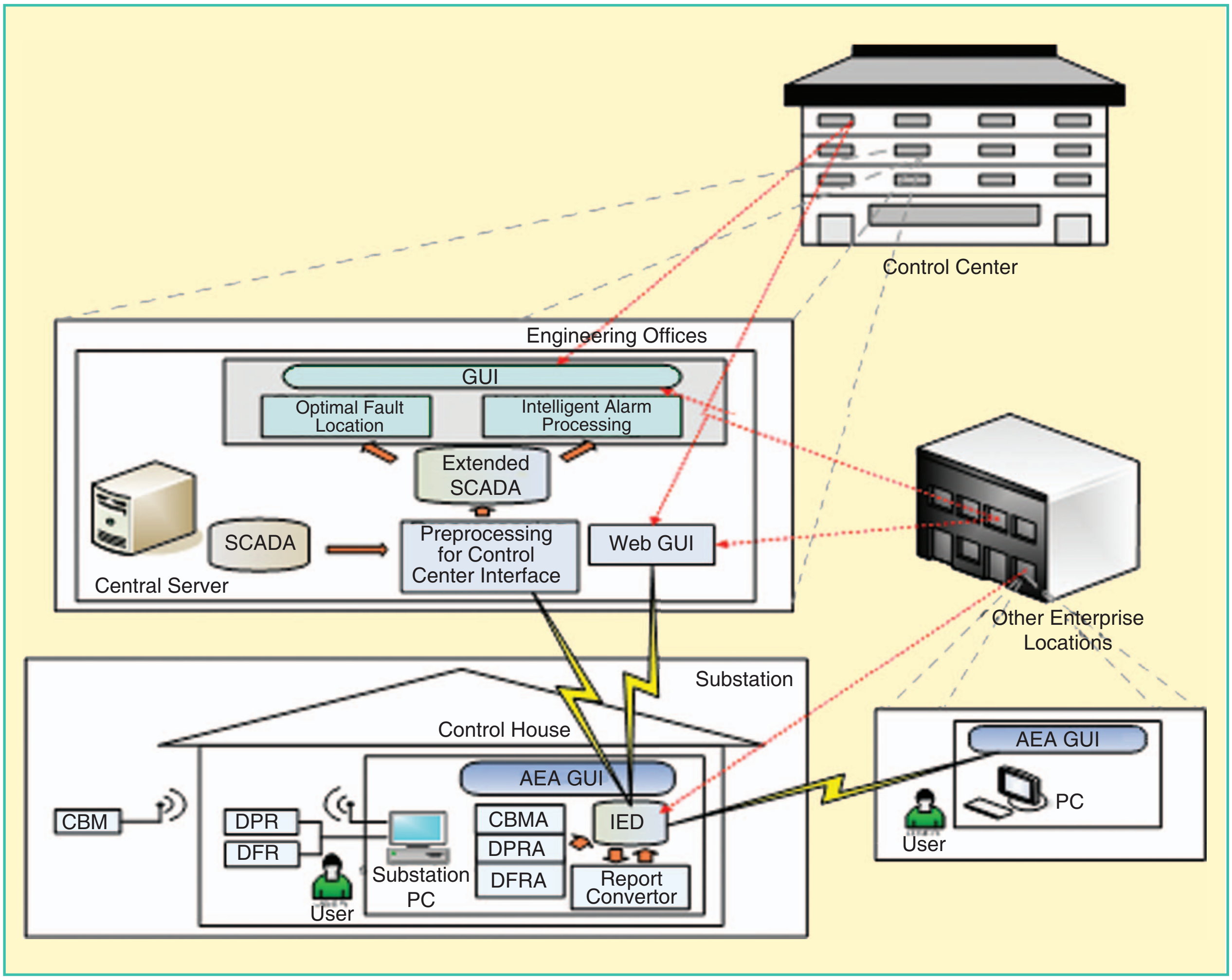


figure 7. The substation data integration and information dissemination architecture.

to their customers. Extruded cross-linked polyethylene insulated cables are employed extensively in the industry. Premature failure of these cables can occur due to aging from exposure to multiple stresses, such as electrical stresses, heat, and chemicals (including water). Furthermore, degraded cables are more susceptible to failure during "dig-ins." To help distribution businesses save on maintenance costs while maintaining reliable service, PSERC university researchers in this study developed a method for assessing the condition of a cable so that cable replacement needs to occur only when the cable approaches the end of its useful life. The extent of degradation can be quantified using two parameters: the area of Fourier transform Infrared

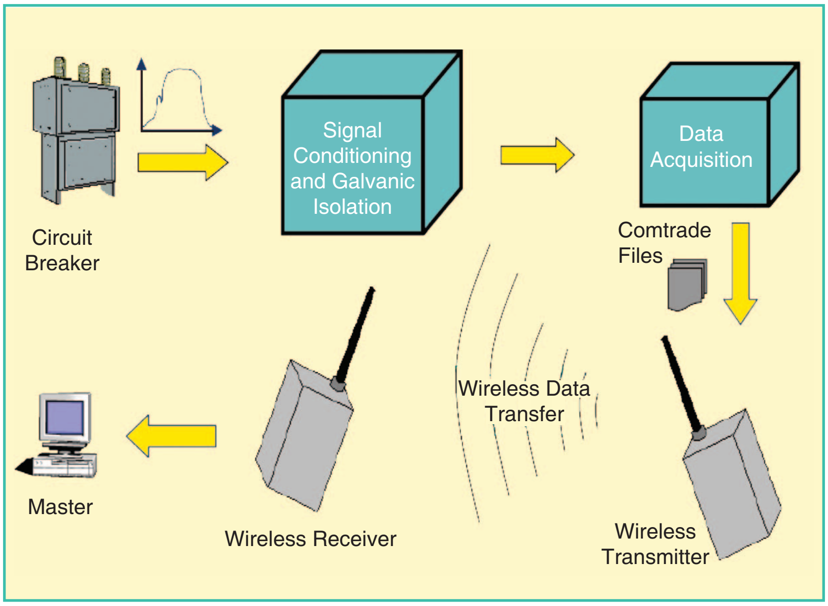


figure 8. Circuit breaker monitoring using a wireless communication system within a substation.

table 2. Sampling of research challenges in distribution engineering recently addressed by PSERC researchers.

Project Title	Project Status
Control and Design of Microgrid Components	Completed 2006
Novel Approach for Prioritizing Maintenance of Underground Cables	Completed 2006
Prediction of Flashover Voltage of Insulators Using Low Voltage Surface Resistance Measurement	Completed 2006
Reliability-Based Vegetation Management Through Intelligent System Monitoring	Completed 2007
Massively Deployed Sensors	Completed 2008
Satellite Imagery for the Identification of Interference with Overhead Power Lines	Completed 2008

spectrum and the electrical breakdown strength using needle plane geometry. Degradation occurring in a hot and dry climate can be reproduced in a laboratory by accelerated thermal aging testing. The Arrhenius equation for the temperature dependence of a chemical reaction rate establishes the accelerated aging test parameters. Utilizing these concepts, modeling and statistical analysis can yield diagnostic methods and estimates of aging. This approach can be used, with reasonable confidence, to prioritize cable replacement and optimize cable maintenance scheduling.

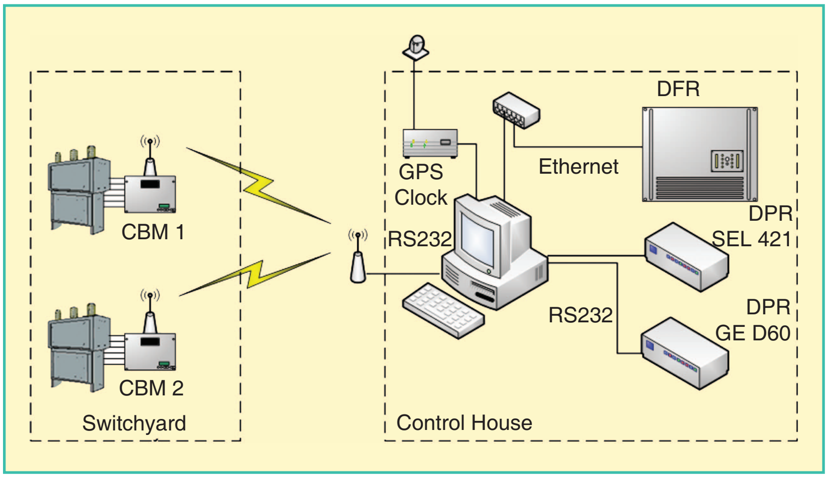


figure 9. GPS-based time synchronization within a substation spanning the field IEDs (CBMs) and control house IEDs (DPRs).

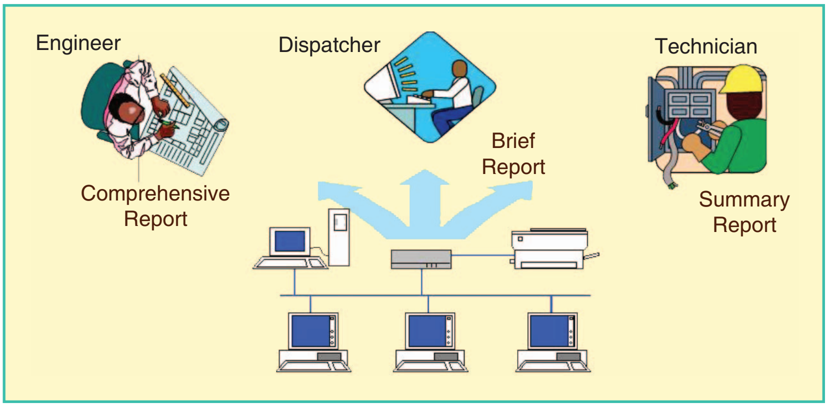


figure 10. Automated distribution of extracted information to various utility groups.

Research Challenges in Systems Engineering

Systems engineering challenges in electric power arise from the massive scale and dynamic nature of electric power grids. The interconnected synchronous power systems of North America and other continents display behavior that couples hundreds of thousands or more pieces of equipment and human organizations, across hundreds and thousands of kilometers, with interactions on times scales from fractions of a second to years. At times of severe system stress, as seen in the August 2003 blackout in the northeastern United States, this wide-area dynamic coupling can propagate cascading failures over great distances at remarkable speed. An important element of the smart grid objective is to supplement this inherent physical and institutional coupling among components and players in the grid, adding "intelligence" that will improve grid performance, security, and efficiency through communications, control, and computation.

A number of the systems-oriented research topics associated with smart grid objectives have a long history but now are poised at an exciting moment when new communications and computer technologies are yielding cost-effective means to achieve earlier visions of transformation in grid performance. Other systems-oriented research objectives within the smart grid, such as improved situational awareness through data mining and visualization, represent largely new directions for the power engineering field. Indeed, a key element of the smart grid vision is the density and ubiquitous communication of system measurements. At a much lower cost than was previously possible, we can extract tremendous detail about grid equipment and system state, and we can communicate that information broadly. The systems engineering challenges in the smart grid include the

> Research in the area of transmission engineering needs to cover many issues across different disciplines, including power engineering, computer engineering, communications, materials, and chemical engineering.

extraction of useful information and the exercise of control strategies that enhance system performance, effectively exploiting this rapidly growing mountain of data.

As an example, systems research in power engineering within PSERC has for many years sought to enhance the grid's ability to respond stably and securely to major disturbances through wide-area monitoring and control. The need for advances in this area has been aptly illustrated in a number of major North American outages, after which post-mortem analyses revealed the potential for wide-area control actions that could have markedly reduced the severity of the blackouts. These opportunities are being expanded by the increasing penetration of synchronized phasor measurement units (PMUs), opening the door to a vastly more detailed operational picture of grid operations. PMUs are among the smart grid technologies that not only create new potential but also raise important research questions as to how this huge volume of new data can best be employed for improving grid reliability and efficiency. Several PSERC research projects have focused on the utilization of PMUs in providing improved visualization, stability control, and monitoring of the power system.

Adaptive islanding is an illustrative example of a research application that marries advances in computational power and high-bandwidth system state measurement (i.e., PMUs) with analytic stability analysis tools. One attractive avenue that has been explored in PSERC projects is to make use of instantaneous phasor measurements to track the system dynamic state in real time, monitoring relative stability and the risk of system separation using the location of the state on a "transient energy function" (TEF) contour. The basic idea consists of evaluating the kinetic energy gained by the machines during the fault period and comparing it with the maximum gain in potential energy that the system can withstand (without becoming unstable) after the fault is cleared. In graphical terms, the system state evolves on the energy function's potential contour, with risk to stability and system separation appearing as the state approaches a low-energy saddle point from which it may escape the stable potential well (analogous to a low-elevation mountain pass out of a valley on a geographic contour map). An illustration of an energy function saddle for a representative 179-bus test system is illustrated in Figure 11. Here, for purposes of visualization, the high-dimensional system state is projected onto just the two degrees of freedom of phase angle and bus voltage magnitude at an individual bus (bus number 107 in the illustration).

Load response is another example of PSERC research that is being greatly enhanced by new technologies. Management of demand-side resources was a research focus through much of the 1980s and early 1990s, but with wireless technologies, such as the ZigBee standard, the means to allow end-use equipment to communicate with facility-level and grid-level control systems have reduced dramatically in cost. Here is a case in which a seemingly quantitative change (cost reduction to achieve communication) has created qualitative changes in what is possible. The basic concept of end-use loads being modified to respond in ways that would enhance grid stability was envisioned by Schweppe in the 1970s; the effective realization of nondisruptive load control awaited today's technologies and will likely be a key element of the smart grid. Some of the research challenges in systems engineering recently addressed by PSERC researchers are listed in Table 3.

Research Challenges in Markets and Finance

The piecemeal deregulation of the electric utility industry in different regions of the nation over the past decade has increased the economic complexity of the issues faced by customers, utility companies, and investors. Despite the fact that the electric delivery system consists of three meshed networks (the Western Interconnection, the Eastern Interconnection, and Texas) over which the pattern of supply is governed by the laws of physics, the regulatory rules that determine the economic conditions faced by utility companies vary substantially among different states connected to the same physical network, particularly on the Eastern Interconnection. Some regions on the Eastern Interconnection, such as the southeastern states, have continued to use conventional regulation, while other regions, such as New England, New York, the Midwest, and the states covered by the PJM Interconnection have established new deregulated markets for generation, even though the regulatory traditions for transmission and distribution have largely been maintained.

The initial focus of PSERC research in markets and finance was on the performance of the new deregulated markets for generation and, in particular, on how to design a market to ensure that the market prices were competitive. Much of this early research used experimental economics to evaluate markets by having individuals—typically, graduate students—represent the suppliers in different forms of the electricity market. This type of research pays real money to

table 3. Sampling of research challenges in systems engineering recently addressed by PSERC researchers.

Project Title	Project Status
Detection, Prevention and Mitigation of Cascading Events – Prototype Implementations	Completed 2008
Effective Power System Control Center Visualization	Completed 2008
Optimal Allocation of Static and Dynamic VAR Resources	Completed 2008
Preventing Voltage Collapse with Protection Systems that Incorporate Optimal Reactive Power Control	Completed 2008
Risk of Cascading Outages	Completed 2008
A Tool for On-Line Stability Determination and Control for Coordinated Operating between Regional Entities Using PMUs	Completed 2008

the participants in proportion to how much they earn as a supplier in an experiment, and it has proved to be an effective way to identify weaknesses in a market design that can be exploited to increase market prices and earnings above competitive levels.

The main results of the research using experimental economics show that suppliers can exploit markets relatively easily when the demand is inelastic (i.e., levels of load do not decrease when prices are high), and a relatively large number of equally sized firms (more than 20) are needed to make a market truly competitive. Since most markets do not have large numbers of firms competing on the margin, elaborate forms of market monitoring have been introduced in deregulated markets to identify and mitigate noncompetitive behavior. PSERC research on market performance, however, shows that active participation by loads in a market is also an effective way to make markets competitive. Hence, an important feature of a smart grid is the support of advanced metering for retail as well as wholesale customers. These meters will provide the real-time information on prices and the two-way communications that will allow appliances and equipment to respond to system conditions in a constructive way that will make markets more competitive, reduce

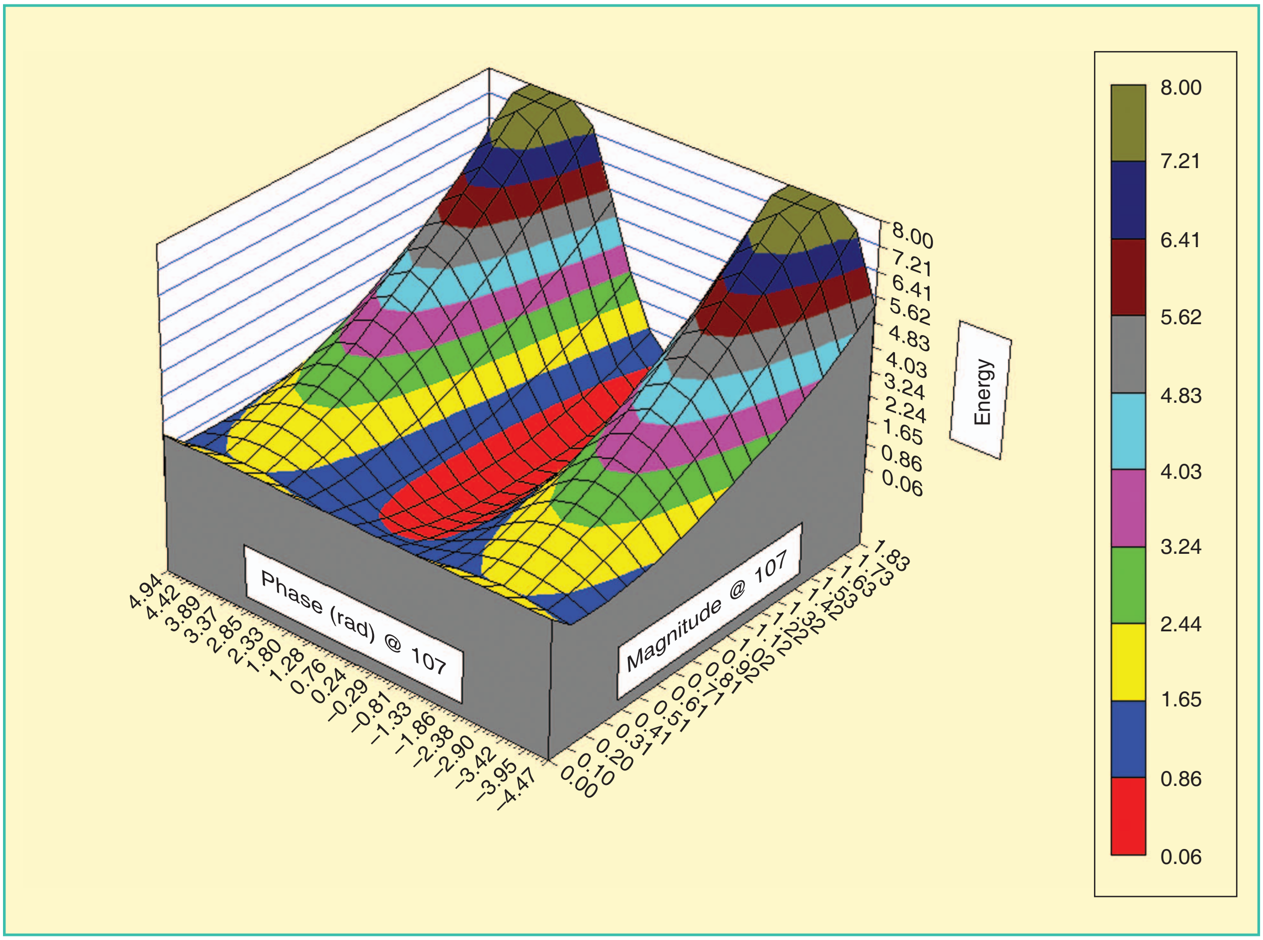


figure 11. Illustration of a saddle point in the energy function (here appearing where the major axis of the red, elliptically shaped "potential well" meets the blue boundary).

congestion on the network, and improve the overall reliability of supply. Smart grids need smart customers to realize the full potential of the new capabilities for managing the electric delivery system.

Additional problems occur with markets when ancillary services are considered. These markets are generally not incentive-compatible because prices can be increased, for example, by withholding capacity from the market to create artificial scarcity. Figure 12 shows the nodal prices paid to six generators for VArs in an experiment that was run for 60 periods. Even though the true competitive prices for VArs are zero, the generators (students) were able to get the market prices substantially above zero by withholding capacity from the market. In this particular example, market power is limited to some extent by allowing loads to reduce their demand for VArs. An effective solution to the problem of market power is to give suppliers both a predetermined income stream for making capacity available and a real-time payment for services delivered. Research has shown that this type of contingent-claim market is preferable for reactive power, and this type of market has been adopted implicitly in the existing capacity markets that have been established in some regions to maintain generation adequacy. However, most retail customers will probably choose not to get involved with an ancillary service market. As a result, aggregators will play an important role on a smart grid by managing controllable loads and distributed energy resources and by purchasing and selling services on the bulk power grid (real power, reactive power, and reserve capacity).

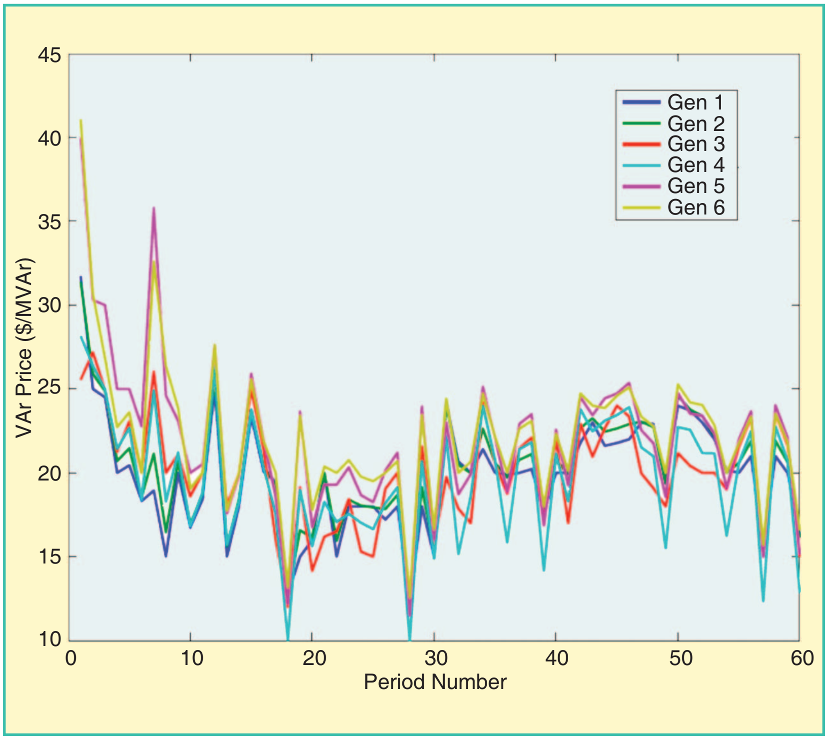


figure 12. Prices for VArs in a market experiment that evaluates the effect of responsive load on market performance.

In a truly competitive market for electricity, some generators may not earn enough income in the wholesale market to remain financially viable (e.g., generating units with low capacity factors that are needed to maintain system reliability). Dealing with this issue of "missing money" is usually the regulatory justification for establishing capacity markets, but the issue is indicative of a more fundamental problem: that merchant investment in new generating capacity has been erratic in deregulated markets. Researchers have investigated the importance of forward markets for investment and the difficulty of establishing these markets for a nonstorable commodity like electricity. In particular, a new paradigm has been developed for planning transmission in a region with a competitive market for generation. This paradigm treats transmission planning as a leading function that anticipates the investment responses of generators and the resulting effects on the wholesale market

table 4. Sampling of research challenges in markets and finance recently addressed by PSERC researchers.

Project Title	Project Status
Uncertain Power Flows and Transmission Expansion Planning	Completed 2007
Electric Power Industry and Climate Change – Discussion Paper	Completed 2007
Modeling Market Signals for Transmission Adequacy Issues: Valuation of Transmission Facilities and Load Participation Contracts in Restructured Electric Power Systems	Completed 2007
Reliability Assessment Incorporating Operational Considerations and Economic Aspects for Large Interconnected Grids	Completed 2007
Reliability, Electric Power, and Public Vs. Private Goods: A New Look at the Role of Markets	Completed 2008
Tools for Assessment of Bidding into Electricity Auctions	Completed 2008
Agent Modeling for Integrated Power System, Power and Fuel Market Simulation	Completed 2008

for energy. Planning for a smart grid should account for the possible countervailing effects of investments made by generators in a competitive wholesale market.

A fundamental property of an electric delivery system is that many characteristics of the services on a meshed network are "public goods" because the benefits are shared among different users. In the same way, harmful emissions from power plants are "public bads"—or external costs that are not reflected in market transactions. Although real energy is a conventional private good, maintaining a high level of reliability has many public-good features. Typically, customers in a market for a public good are willing to pay less than the socially efficient amount, and as a result, additional rules are needed for governing market behavior (enforcing a minimum reserve margin for generation adequacy, for example). Much of the research on ancillary services and reliability has focused on how these rules should be specified and implemented and on the implications for market performance. Current research using a contingency-constrained dispatch (the "SuperOPF") to study system reliability in a planning context shows that the true economic cost per MW of meeting the peak system load is much higher than conventional analyses suggest. Research on smart grids should include determining the correct financial incentives for maintaining system reliability at socially optimal levels. Some of the research challenges in markets and finance recently addressed by PSERC researchers are listed in Table 4.

Looking ahead, it is likely that public concern about environmental issues, such as climate change, will have direct implications for electricity markets. Some of these new developments, such as paying a price for emitting carbon dioxide, will affect the relative costs of different types of generation but will not require changes to the basic structure of the wholesale market. Others, such as the increased importance of renewable sources of energy on a network, will have major effects on system operations. Current PSERC research is addressing these developments by studying, for example, how controllable load and storage can be used to offset the intermittent nature of wind generation. Another project is using the SuperOPF to evaluate the effects of additional environmental costs and constraints (including the geographic movement of pollutants and regional ambient levels of pollutants); the project is modeling carbon dioxide, ozone, and fine particulates to determine the minimum social cost of operating the system and how the regional patterns of dispatch and emissions are affected. For example, demand response through smart appliances and smart metering could be an efficient way to meet the eight-hour ozone standard that is consistently violated in urban areas across the United States. The capabilities of a smart grid will be essential for meeting these new environmental challenges while at the same time maintaining overall system efficiency and reliability.

The Role of the University Consortium

Modern power engineering entails challenges not seen in this field in the past. One way to address research challenges is to utilize the capability of universities—both their student researchers and faculty. This concept effectively leverages funds that are targeted for power engineering. The idea of a university consortium— a "collaboratory" of several universities and many researchers and students—has been discussed. Topical areas in power markets, transmission and distribution, and power systems have been identified. Perhaps the greatest value of using a consortium strategy to address power engineering research is the value of educating and training the engineers who will face these challenges.

Acknowledgments

The authors acknowledge the research work and input from the approximately 35 researchers who work with PSERC at one of the center's 13 member universities. Acknowledgment is also due to 40 industrial sponsors as well as the United States Department of Energy.

For Further Reading

M. Kezunovic and A. Abur, "Merging the temporal and spatial aspects of data and information for improved power system monitoring applications," *Proc. IEEE*, vol. 9, no. 11, pp. 1909–1919, 2005.

J. W. Stahlhut, G. T. Heydt, and N. J. Selover, "A preliminary assessment of the impact of ambient temperature rise on distribution transformer loss of life," *IEEE Trans. Power Delivery*, vol. 23, no. 4, pp. 2000–2007, Oct. 2008.

F. C. Schweppe, "Power systems 2000: Hierarchical control strategies," *IEEE Spect.*, vol. 15, no. 7, pp. 42–47, July 1978.

N. Senroy, G. Heydt, and V. Vittal, "Decision tree assisted controlled islanding," *IEEE Trans. Power Syst.*, vol. 21, no. 4, pp. 1790–1797, Nov. 2006.

Markets for reactive power and reliability: A white paper. Engineering and Economics of Electricity Research Group (E3RG), Cornell Univ., Dec. 2006. [Online]. Available: http://e3rg.pserc.cornell.edu/

PSerc Reports [Online]. Available: http://www.pserc.org/ecow/get/publicatio/reports/

Biographies

Mladen Kezunovic is the Eugene E. Webb Professor in the Department of Electrical Engineering at Texas A&M University.

Gerald T. Heydt is a Regents professor at Arizona State University.

Christopher DeMarco is a professor of electrical and computer engineering at the University of Wisconsin-Madison.

Timothy Mount is a professor in the Department of Applied Economics and Management at Cornell University. p&e