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The Grid of the Future Workshop Summary Report

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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The Grid of the Future Workshop Summary Report

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Abstract

The Grid of the Future was a one-day workshop to discuss a resilient grid for the 21st and 22nd century. The workshop gathered experts from various fields to explore concepts for the electric power grid of the future with an emphasis on improving resilience. The event was co-sponsored by Sandia National Laboratories, the Albuquerque IEEE Section, the University of New Mexico, New Mexico State University, and the Santa Fe Institute. The presenters identified radical changes to the grid that are expected to occur over the next 25-50 years and the role of resilience. The workshop was held at the University of New Mexico on Wednesday, August 22nd, 2018. This report summarizes presentations and discussions from the workshop.

ACKNOWLEDGMENTS

The authors would like to thank all of the presenters and session chairs who prepared insightful and informative briefings on R&D challenges and opportunities for electric grid of the future, as well as all the participants for their contributions to the workshop. In addition, the authors would like to thank all the supporting staff that made the workshop such a success.

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1. EXECUTIVE SUMMARY

The Grid of the Future was a one-day workshop to discuss a resilient grid for the 21st and 22nd century.

This workshop gathered experts from various fields to explore the electric power grid of the future, with an emphasis on improving resilience. Co-sponsored by Sandia National Laboratories, the Albuquerque IEEE Section, the University of New Mexico, New Mexico State University, and the Santa Fe Institute, the workshop discussed radical changes to the grid occurring over the next 25-50 years and beyond and the role of resilience. In addition, the workshop featured presentations from invited speakers on multiple grid-of-the-future topics.

The purpose of this workshop was to increase collaboration in the area of grid resilience from multiple organizations, stimulate discussion, and learn from some of the greatest minds in the field to improve our awareness to the need for a resilient grid of the future, and improve our knowledge of the subject.

The workshop consisted of two introductory speakers from Sandia National Laboratories and The University of New Mexico. This was followed by a keynote presentation on reliability versus resilience and how previous events can help us prepare for the future. Next the workshop consisted of five panel sessions, each session included three distinguished presenters followed by a panel discussion.

1. The first session covered grid interdependencies with critical infrastructure, and presentations and discussion focused on gas-grid interdependencies, and how to co-develop a power grid and gas network with resilience in mind. The session also discussed vulnerabilities in the power grid and how to identify and improve the weakest points of the electric grid.

2. The second session covered resilient distribution systems. Discussion and presentations leaned toward protection for distribution systems and how a properly designed protection system can significantly improve grid resilience including partitioning the grid into microgrids during catastrophic events. The session also discussed how system awareness is important during large scale events, and methods to improve a utility's ability to gather information and act on that information during events.

3. The third session covered the evolution of control centers and integrating renewables. The presentations and discussion highlighted the need for control strategies to be developed for distributed energy resources (DER) to improve reliability and resilience. In addition, the panel discussed interconnection requirements for DER and how islanded distribution systems during major events may improve resilience. Lastly, the panel described how control centers, energy management systems (EMS), and distribution management systems, including

automation and sectionalizing, can increase system awareness through measurement devices and advanced communication.

4. The forth session covered electromagnetic pulse (EMP) resilience. The discussion focused on power system devices and their failure probabilities during EMPs, how cascading outages can occur after an EMP scenario, and how to determine the most vulnerable parts of a network. In addition, dialogue was on infrastructure improvements to improve resilience, and the social and economic impacts EMPs may have on a society.

5. The last session covered grid stability. The presenters made the case that models and modeling tools need to be updated to better represent the future grid, including increased renewables and cascading outage analysis. The challenges when modeling inverter based generation versus conventional rotating generation were discussed, along with how these changes will affect future resilience. This led to a discussion of how a modeling tool can accurately model a 100% inverter based generation portfolio. to the panel also covered how control systems and wide area measurements will be important tools for the grid of the future. Lastly, there was discussion on how to improve stability margins using machine learning and optimization approaches.

Following the panel sessions, concluding remarks were given before a social reception for people to meet one on one and further collaborations.

The meeting was structured to encourage interaction and discussion of the grid of the future.

This report provides an overview of the workshop contents and summarizes the key discussion and outputs. Presentation slides are included on the workshop website.

2. NOMENCLATURE

AC	Alternating Current
DC	Direct Current
DER	Distributed Energy Resources
DOE	U.S. Department of Energy
EMP	Electromagnetic Pulse
EMS	Energy Management System
PV	Photovoltaic

3. WORKSHOP SUMMARY

3.1. Keynote Speaker: Robert Cummings, *North American Electric Reliability Corporation (NERC)*

The keynote presentation focused on how changes to the grid will impact system reliability and resilience and how previous events and changes to the grid can help us prepare for the future.

The grid of the future will face the transition challenges including:

- Higher levels of inverter-based resources reduce inertia and synchronizing torque creating instability issues

- Reduction in fault current provided by inverters requires system protection redesign.

- Not all areas can locally support renewable energy therefore transmission and energy storage are critical.

- Load will significantly change, which is no longer adequate for simulation.

The changes in generation mix and load profile create a significant need for energy storage. As a very fast and flexible resource, energy storage could provide high-speed energy injection for frequency response or ramp rate support thereby offsetting the loss of system inertia. The grid of the future must have the capability to tolerate the loss of large renewable power plants. Lessons learned from the past recommend the following mitigating actions: dynamic model improvements, mitigation of momentary cessation, plant control-loop coordination, information sharing among operating entities. Planning and operation studies are critical to ensure no potential stability risks.

In summary, the "grid of the future" will face a huge control problem (interactions of controls, system protection, interactions between new and old resources/loads). The current analysis tools are not sufficient to study those interactions. "The changes are happening YESTERDAY and the grid of the future is as SMART as we make it."

3.2. Session 1: Grid Interdependencies with Critical Infrastructure

Chair: Brian Pierre, *Sandia National Laboratories*
Panelists:

- Russell Bent, *Los Alamos National Laboratory*
- Seth Blumsack, *Penn State University*
- Charles Macal, *Argonne National Laboratory*

The first session explored how the electric power grid is dependent on critical infrastructure. The presenters addressed the questions of: What role does critical infrastructure have in the grid of the future? How does critical infrastructure need to change or adapt for the grid of the future? What key challenges need to be addressed to enable the grid of the future given its interdependencies with critical infrastructure? How does one assign value to resilience?

At a high level, multiple critical sectors have infrastructure interdependencies including electricity, transportation, water, oil, natural gas, and communications sectors. This is a very diverse set of stakeholders. In the past, the electric power industry has adapted, withstood, and recovered from a constant changes and challenges. In the future, we can imagine that our equipment, systems, and infrastructure will do the same.

It is crucial to model the grid interdependencies with other critical infrastructures such as oil, gas, transportation, water, communications/IT to understand the system risk. Critical infrastructure modeling is required in disaster planning, emergency response, and community recovery. The current analysis tools are inadequate and new tools are needed for grid operational analysis, risk and resilience evaluation.

In general, improving resilience can be thought of as improving a system's capability to reduce the magnitude and duration of contingencies. Planning for resilience of natural gas systems and electric grid is crucial because failures in the natural gas infrastructure can propagate to the electric power sector, and vice versa. Furthermore, prices and demand for natural gas can affect electricity prices and demand, and vice versa. Consequently, natural gas variability is increasing beyond historical norms, largely driven by the electric power sector. Currently, gas and power transmission have very different planning and price formation processes in the United States. A necessary approach to increase for reliability and resilience for the future, then, is to reduce risk through coordinated design and operations of both natural gas and electric power infrastructure. Therefore, improved models of interdependent infrastructure, in particular the natural gas and electric power grid, are crucial for understanding, and ultimately mitigating, systemic risk.

How can one quantify the value of reducing risk? For instance, how can owners of resources that reduce the risk of blackout be fairly compensated? The potential value provided by a resource may take many forms depending on the location, other resources, population, etc. affected by the blackout. However, we can get some general ideas from investigating statistical risk models for social and private values of risk reduction. Ultimately, a future grid with a larger amount of distributed generation can provide measurable reliability benefits. Moreover, services such as demand response and capacity markets are two ways that owners of distributed generation can realize some of this value. In the future, additional programs or incentives should be designed and implemented to incentivize and fairly compensate the value of reducing systemic risk.

3.3. Session 2: Resilient Distribution Systems

Chair: Matthew Reno, *Sandia National Laboratories*
Panelists:

- Sukumar Brahma, *New Mexico State University*
- Satishkumar Ranade, *New Mexico State University*
- Chen-Ching Liu, *Virginia Tech University*

The second session focused on distribution systems and the growing need to make them resilient to a myriad of contingencies, such as extreme weather events, cyber-attacks, and physical security threats. Current distribution grids are going through a significant transformation. Devices such as smart meters and automated metering infrastructure are being widely deployed. Microgrids are being designed, and the ability to break apart large systems into individual microgrids continues to be explored. New entities for demand response and energy aggregation are emerging. The transportation sector is becoming more electrified as the number of electric vehicles increases. All of these changes are leading to enhanced monitoring and prediction capabilities for outages, restoring systems by remote control and automation, and generally improved resilience to contingencies.

For example, the advent of microgrids supports fast recovery of distribution systems. Microgrids can be controlled to provide efficient system restoration of critical loads and improve overall resilience. Distributed generators can be used to absorb transient behavior and maintain stability. Due to scarcity of fuels for generators after an extreme contingency, other resources, like energy storage, will be crucial to realize a high level of resilience. Resources like energy storage will also enable effective islanding in which power for critical loads and resources can be maintained.

There has been substantial growth of renewable generation in distribution grids. Thus far, the largest growth has been in solar generation. With massive growth in distributed generation in distribution grids, there will be many opportunities for new entities, like energy aggregators, to provide services like demand response and frequency regulation or bid into wholesale energy markets in the same way that utilities do. In general, distributed resources connected to the grid via a power electronic interface can provide real and reactive power and participate in energy transactions.

Other emerging technologies have the potential to greatly affect future distribution grids. More electric vehicles may cause large uncertainty in connected load but have the potential to provide vehicle-to-grid services. Smart inverters and the internet of things will be disruptive technologies that enable further demand response and load management. Ultimately, policies and operating structures will define the engineering approaches to addressing challenges associated with design, operation, and risk and resilience related to these emerging technologies and the future distribution grid.

3.4. Session 3: Evolution of Control Centers and Integrating Renewables

Chair: Ali Bidram, *University of New Mexico*
Panelists:

- Reinaldo Tonkoski, *South Dakota State University*
- Anjan Bose, *Washington State University*
- Babak Enayati, *National Grid*

Session 3 focused on two areas: what future control centers will look like, and how increasing penetration of renewable generation affect grid resilience.

With the advent of increased sensing capabilities, for example with the wide deployment of phasor measurement units in the transmission grid or the advanced metering infrastructure in distribution systems, measurements can be sampled at very high rates, time-stamped, and communicated more readily than ever before. These measurements allow for real-time monitoring and control of the grid. Therefore, with additional sensing and control capabilities and requirements, data rates for control centers in the future could increase two or three orders of magnitude. All the additional sensors and data need to be managed in a way the control center operators can use this improved system visibility to make better choices and uphold the power system even during large scale events.

One topic discussed was the opportunities for a future interconnected grid. The future interconnected grid allows for many opportunities including improved economics, since energy can be more easily transferred from areas where it is cheap to where it is expensive, and improved reliability, since more resources will provide redundancy.

As generation will become more renewable and distributed, distribution management systems need to evolve with higher level of control and monitoring such as more measurements along the feeders, remote control of transformer taps and sectionalizers, better voltage control, advanced communication network. Distributed energy resource management systems are mostly used today for demand response. However, in the future, they could enable the aggregation of residential resources such as roof-top solar, water heaters. In such management systems, advanced metering and communication are the key infrastructures for the optimal operation (high efficiency and low cost) of the grid. Outage management system will be much more computerized requiring less people to handle customers calls or to do crew dispatching. Building automation enabled by smart metering will help customers minimize the energy cost and increase PV and energy storage deployment. To achieve this vision, a holistic systems approach is needed for operating the grid. This approach will be driven by the utilities and the regulators. It requires more R&D to improve and create new technologies, tools, and institutional policies to promote solutions to improve grid resilience under uncertainty.

Renewable penetration will continue to increase. Because of this, there is a concern about the stability of the future electric power grid. Fewer large, rotating machines will be present to provide inertia for the system. However, with more flexible and controllable resources connected to the grid via power electronics, there is the opportunity to more quickly and robustly stabilize the grid by providing virtual inertia or by having the capability to rapidly increase or decrease power levels. This ability requires research into modeling and control of distributed resources. Furthermore, renewable generation is inherently intermittent and random because it can largely depend on weather. The ability to accommodate and mitigate the challenges arising from random and intermittent generation will be key for the successful massive integration of renewables. This will require further research into forecasting and real-time control of many distributed resources.

3.5. Session 4: EMP Resilience

Chair: Jason Neely, *Sandia National Laboratories*
Panelists:

- Jane Lehr, *University of New Mexico*
- Olga Lavrova, *Sandia National Laboratories*
- Charles Bayless, *The Climate Institute*

The resilience of the electric power grid is of critical importance. The susceptibility of the electric power grid to an electromagnetic pulse (EMP) is a very complex problem that is not completely understood because it requires integrated work across multiple technical fields. The EMP threat to the electric grid should be comprehensively studied to create deeper understanding of vulnerabilities, failure modes and consequences. Technological solutions including new materials and device development are needed to harden critical infrastructure of the grid. Operational and optimization solutions are essential to improve grid resiliency.

The consequences of a large scale EMP event was discussed, including economic loss, societal loss, and loss of life. With such drastic impacts, research on mitigation of these consequences is imperative. Discussion on the EMP event was wide, from specific device failures to how the device failures can lead to cascading outages. Methods to model these failures and the cascading outage effect need to be better understood, and tools for these purposes need to be developed. Lastly, identifying the most vulnerable components and locations to an EMP event can help determine optimal investment locations to mitigate the consequences.

3.6. Session 5: Grid Stability

Chair: David Schoenwald, *Sandia National Laboratories*
Panelists:

- Daniel Trudnowski, *Montana Tech University*
- John Undrill, *Arizona State University*
- Ross Guttromson, *Sandia National Laboratories*

As the grid evolves, more generation will have electronic interface. The speakers pondered the question: will we be able to operate an all-electronic grid with the current practices and simulation tools? The simulation and analysis tools have contributed to the understanding of the behaviors of the bulk power systems and vice versa. They require highly-detailed information on how power plants and other power system devices are operated. The modern grid simulation tools, e.g., PSS/E and PSLF, (which were in part developed by one of the presenters in this session, Dr. John Undrill) are not capable of dealing with the problems associated with an all or mostly electronic generation system. Hardware-in-the-loop (for control elements) and power-hardware-in-the-loop (for power elements) simulations and full-power testing of power plants' inverters will be highly needed. In addition, once hardware testing is more thoroughly understood, models and modeling tools are needed to be able to simulate large scale power systems with primarily electronic based generation.

Further discussion focused on power system controls and power transfer limits with increased inverter based generation. Simple models were used to demonstrate stability limits with and without inverter based generation, and with and without fast controls. Conclusions indicate, very fast control systems with limited delay are necessary to maintain system stability with a high penetration of inverter based generation. In addition, the deployment of wide-area measurement systems enable many active control techniques to improve system stability.

Increased renewable generation has the possibility of decreasing stability margins and pushing existing infrastructure closer to its limits. This could have a negative impact on power system resilience. Stability margins can be improved by changing the system state based on machine learning and optimization. If the system is in a state with low stability margins (there are many types of stability margins, e.g. voltage stability margin, transient stability margin, system droop margin), how can you improve the margins in the most optimal way. Utilizing historical data and machine learning algorithms it may be possible to formulate an optimization model to improve stability margins and improve power system resilience.

APPENDIX A – GRID OF THE FUTURE WORKSHOP AGENDA

Wednesday August 22, 2018		
8:00	Registration, coffee, and continental breakfast	
8:30	Welcome	Christos Christodoulou, *University of New Mexico, Jim and Ellen King Dean of Engineering and Computing*
8:40	Introductory Remarks	Carol Adkins, *Sandia National Laboratories, Director, Energy, Earth, and Complex Systems*
8:50	Keynote Speaker	Robert Cummings, *North American Electric Reliability Corporation (NERC),* Grid Reliability
9:20	Session 1: Grid Interdependencies with Critical Infrastructure	Chair: Brian Pierre, *Sandia National Laboratories* Panelists: Russell Bent, *Los Alamos National Laboratory,* Gas-Grid Resilient Design Seth Blumsack, *Penn State University,* Identifying Vulnerable Critical Infrastructure Charles Macal, *Argonne National Laboratory,* Grid-Critical Infrastructure Interdependencies
10:35	Break	
10:45	Session 2: Resilient Distribution Systems	Chair: Matthew Reno, *Sandia National Laboratories* Panelists: Sukumar Brahma, *New Mexico State University,* Power System Protection in the Era of Smart Grid Satishkumar Ranade, *New Mexico State University,* R2- Risk Aware, Resilience Aware Management of Energy Delivery Chen-Ching Liu, *Virginia Tech University,* Resilient Distribution Systems
12:00	Lunch	
1:00	Session 3: Evolution of Control Centers and Integrating Renewables	Chair: Ali Bidram, *University of New Mexico* Panelists: Reinaldo Tonkoski, *South Dakota State University,* Voltage Control Strategies for Distribution Systems with High Penetration of Photovoltaics Anjan Bose, *Washington State University,* Evolution of Control Centers for the Future Grid Babak Enayati, *National Grid,* DER Interconnection Requirements in Islanded Distribution Systems
2:15	Break	
2:30	Session 4: EMP Resilience	Chair: Jason Neely, *Sandia National Laboratories* Panelists: Jane Lehr, *University of New Mexico,* EMP Resilience at the Grid of the Future Olga Lavrova, *Sandia National Laboratories,* EMP Grand Challenge Charles Bayless, *The Climate Institute,* The North American Super Grid Project

3:45	Break	
4:00	Session 5: Grid Stability	<u>Chair:</u> David Schoenwald, *Sandia National Laboratories* <u>Panelists:</u> Daniel Trudnowski, *Montana Tech University,* Passive versus Active Grid Reliability John Undrill, *Arizona State University,* Power and Frequency Control in the Grid of 2050 Ross Guttromson, *Sandia National Laboratories,* Mapping Power System Stability Using Machine Learning
5:15	Closing Remarks	Charles Hanley, *Sandia National Laboratories*
5:20	Reception	
7:30	Adjourn	

APPENDIX B – GRID OF THE FUTURE WORKSHOP ATTENDEE LIST

First Name	Last Name	Affiliation
Adam	Summers	Sandia National Labs
Alexander	Headley	Sandia National Laboratories
Alfred	Florence	Colorado EMP Task Force
Amanda	Dodd	Sandia National Laboratories
Amy	Halloran	Sandia National Laboratories
Ankith	Nadella	New Mexico State University
Babak	Enayati	National Grid
Babu	Chalamala	Sandia National Laboratories
Benjamin	Karlson	Sandia National Laboratories
Brian	Pierre	Sandia National Laboratories
Brian	Naughton	Sandia National Laboratories
Bryan	Arguello	Sandia National Labs
Bryan	Arguello	Sandia National Labs
Carol	Adkins	Sandia National Laboratories
Charles	Macal	Argonne National Laboratory
Charles	Hanley	Sandia National Laboratories
Charles	Bayless	self
Christian	Gould	Sandia National Laboratories
Christine	Lai	Sandia National Laboratories
Craig	Collier	Green Energy Resources and Services
Craig	Lawton	Sandia National Laboratories
Dan	Trudnowski	Montana Tech
Daniel	Borneo	Sandia National Laboratories
David	Schoenwald	Sandia National Laboratories
David	Copp	Sandia National Laboratories
David	Rosewater	Sandia
David	Sokoloff	Sandia National Labs
Deborah	Neuman	retired
Eduardo	Ortiz-Rivera	University of Puerto Rico-Mayaguez
Erick	Aponte-Bezares	UPRM
Erin	Engelbrecht	City of Albuquerque
Felipe	Wilches-Bernal	Sandia National Laboratories
FRANK	CURRIE	Sandia National Labs
Gary	Oppedahl	Emera Technologies
Geoff	Klise	Sandia National Labs
Gerhardus	Prinsloo	UNM
Irene	Trujillo	Sandia

Jacquelynne	Hernandez	Sandia National Labs
Jason	Neely	Sandia National Labs
Javier	Hernandez-Alvidrez	New Mexico State University
Jay	Johnson	Sandia National Laboratories
Jeffrey	Koplow	Sandia National Labs
Jennifer	Kirby	PomTech Ltd
Jimmy	Quiroz	Sandia National Laboratories
Jock	Embry	La Mesa Water Cooperative
John	Undrill	JMU
Kelvin	Lai	Vertiv
Kevin	Dunn	Sandia National Laboratories, Wind Energy Department
Laura	Moorefield	Moorefield Research & Consulting
Marco	Ortiz	NMSU Facilities and Services
Mark	Petri	Argonne National Laboratory
Matthew	Reno	Sandia National Labs
Matthew	Thompson	Sandia National Laboratories
Matthew	Hoffman	Sandia National Laboratories
Melissa	Coverdale	UNM NM EPSCoR
Michael	Bynum	Sandia National Laboratories
Michael	Baca	Sandia National Laboratories
Michael	Brumbach	Sandia
Mollye	Wilson	Sandia National Labs
Murali	Baggu	National Renewable Energy Laboratory
Nataraj	Pragallapati	New Mexico State University
Olga	Lavrova	Sandia National Labs
Paul	Clem	Sandia National Labs
Rakeshkumar	Mahto	California State University
Randy	Brost	Sandia National Laboratories
Raymond	Byrne	Sandia National Laboratories
Reinaldo	Tonkoski	South Dakota State University
Robert	Jeffers	Sandia National Laboratories
Ross	Guttromson	Sandia
russel	waymire	Sandia National Laboratories
Ryan	Elliott	Sandia National Laboratories
Sandra	Begay	Sandia National Labs
Satish	Ranade	New Mexico State University
Shamina	Hossain-McKenzie	Sandia National Laboratories
Sharon	Ruiz	Sandia National Laboratories
Stan	Atcitty	Sandia National Laboratories
Stephen	Cohn	Hyperloop Advanced Research Partnership
Sukumar	Brahma	Clemson University
Susan	Adams	Sandia National Labs

Suzette	Srader	Sandia National Laboratories
Todd	Monson	Sandia Labs
Tu	Nguyen	Sandia National Laboratories
Wayne	Staats	Sandia National Labs
William	Kwan	Honeywell International Inc.
Yuliya	Preger	Sandia National Labs

APPENDIX C – SPEAKER BIOGRAPHIES

Carol Adkins is Director of the Energy, Earth, and Complex Systems Center at Sandia National Laboratories in Albuquerque, New Mexico. Carol provides leadership and management direction for Sandia's applied energy, grid, and geoscience research and development programs. Previously, Carol was Director of the Energy Technologies and System Solutions Center, overseeing all of Sandia's renewable-energy and grid programs. Some of her past management roles include Director of Materials Science and Engineering; Deputy Director of the Nuclear Weapons Science and Technology Strategic Area with responsibility for the National Nuclear Security Administration's science and infrastructure funding at Sandia; and Principal Program Director for the Defense Security Program, including all physical and cyber security at Sandia.

Charles Bayless is a retired Utility Executive and University President. Until June 30, 2008, Mr. Bayless was President and Provost of the West Virginia University Institute of Technology, a divisional Campus of West Virginia University. Prior to Dec 27, 1999 Mr. Bayless specialized in troubled utility restructuring and was Chairman, President, and Chief Executive Officer of Illinova Corporation. Mr. Bayless was Senior Vice President and Chief Financial Officer of Public Service Company of New Hampshire where he guided the company through the first bankruptcy of a large utility. Before that, he was employed by Consumers Power Company in Jackson, Michigan, first as an attorney, then as the Director of Nuclear Fuel Supply, and finally as the Director of Special Corporate Projects. Mr. Bayless received his BSEE from West Virginia Institute of Technology in 1968. In 1971, he earned his MSEE, in power engineering, and in 1972 his law Degree, both from West Virginia University.

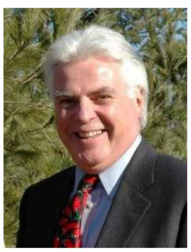
Russell Bent received his Ph.D. degree in computer science from Brown University in 2005. Since then he has been a scientist at Los Alamos National Laboratory. He is currently in the Applied Mathematics and Plasma Physics Group (T-5), where he leads LANL's inter-organizational Advanced Network Sciences Initiative (ANSI). Dr. Bent is the principal or co-principal investigator for numerous DOE projects in infrastructures systems with focuses on improving robustness of infrastructure systems to extreme events, increasing resilience of distribution networks, modeling interdependencies between systems, managing disasters that impact critical infrastructure, modeling smart grid technologies, and developing methods for mixed-integer, non-linear optimization. He is the lead developer for the software POD, A Global Solver for Nonconvex MINLPS and the software GasModels.jl, a toolbox for modeling natural gas systems. He is the author of one book, *Online Stochastic Combinatorial Optimization*, and over 80 peer reviewed journal and conference publications. Dr. Bent is also an associate editor for the INFORMS Journal of Computing.

Seth Blumsack is Professor of Energy Policy and Economics and International Affairs in the John and Willie Leone Family Department of Energy and Mineral Engineering at Pennsylvania State University. His research interests include the intersection of engineering, economics, and the regulation of energy and electric power systems. He is currently on the External Faculty of the Santa Fe Institute and is an Adjunct Research Professor with the Carnegie Mellon Electricity Industry Center. He holds a BA degree in mathematics and economics from Reed College, and MS and PhD degree in economics and engineering and public policy, respectively, both from Carnegie-Mellon University.

Anjan Bose received the B.Tech. degree from the Indian Institute of Technology (IIT) Kharagpur, Kharagpur, India, the M.S. degree from the University of California, Berkeley, CA, USA, and the Ph.D. degree from Iowa State University, Ames, IA, USA. He has worked for industry, academe, and government for 40 years in electric power engineering. He is currently a Regents Professor and also an endowed Distinguished Professor of Power Engineering at Washington State University, Pullman, WA, USA, where he also served as the Dean of the College of Engineering and Architecture during 1998–2005. Dr. Bose is a member of the U.S. National Academy of Engineering and a Foreign Fellow of the Indian National Academy of Engineering. He received the Herman Halperin Award and the Millennium Medal from the IEEE and was recognized as a distinguished alumnus by IIT Kharagpur and Iowa State University.

Sukumar M. Brahma received the B.Eng. degree in electrical engineering from Gujarat University, Ahmedabad, India, in 1989, the M.Tech. degree in electrical engineering from the Indian Institute of Technology, Bombay, in 1997, and the Ph.D. degree in electrical engineering from Clemson University, Clemson, SC, in 2003. From 1990 to 1999, he was a Lecturer in the Electrical Engineering Department at Birla Vishvakarma Mahavidyalaya Engineering College, Vallabh Vidyanagar, India. From 2003 to 2007, he was Assistant Professor at Widener University, Chester, PA. From 2008 to 2018 he was a faculty at New Mexico State University, Las Cruces, where he became the William Kersting Endowed Chair Professor. He is currently the South Carolina Electric & Gas Distinguished Professor at Clemson University. Dr. Brahma is the past Chair of IEEE Power and Energy Society's Life Long Learning Subcommittee, past Chair of Distribution System Analysis Subcommittee, past Chair of Power and Energy Education Committee, and a member of the Power System Relaying Committee (PSRC). He is an editor for IEEE Transactions on Power Delivery, and served as Guest Editor-in-Chief for the Special Issue on Frontiers of Power System Protection for the journal.

Christos Christodoulou served as the chair of the Electrical and Computer Engineering Department from 1999 to 2005. He is a Fellow member of IEEE, a member of Commission B of URSI, an IEEE AP-S Distinguished Lecturer (2007-2010), and a Distinguished Professor at UNM. Currently, he is the Dean for the School of Engineering and Computing. He has advised over 30 Ph.D. students and over 70 M.S, has published over 500 papers in journals and conferences, has 17 book chapters and has co-authored 8 books. He is one of the founders of UNM's COSMIAC (formerly the Configurable Space Microsystems Innovations & Applications Center), serving as its director from 2012 to 2014. Christodoulou is an IEEE Fellow and has received a variety of awards and honors over the years for his work, including the 2010 IEEE John Krauss Antenna Award for his work on reconfigurable fractal antennas, the IEEE Outstanding Engineering Educator in 2012 (Albuquerque section), and was inducted in the Alumni Hall of Fame for the Department of Electrical and Computer Engineering at North Carolina State University in 2016. He was appointed an IEEE AP-S Distinguished Lecturer from 2007 to 2010.



Robert W. Cummings – NERC Senior Director of Engineering and Reliability Initiatives. Mr. Cummings joined NERC in 1996 and has extensive experience in the industry in system planning, operations engineering, and wide area planning. He holds a Bachelor of Science Degree in Power System Engineering from Worcester Polytechnic Institute and is an IEEE Senior Member. He is a member of the U.S. Department of Energy (DOE) Energy Advisory Committee, and its Energy Storage and Smart Grid Subcommittees. Cummings is also a member of the Scientific Advisory Board of CURENT (Center for Ultra-wide Area Resilient Electric Energy Transmission Networks), a National Science Foundation and Department of Energy Engineering Research Center. His geographically diverse experience includes Central Vermont Public Service Corporation in System Planning (generation and transmission), Public Service Company of New Mexico (Operations Engineering and Wide Area Planning), and the East Central Area Reliability Coordination Agreement (ECAR), a former regional office of NERC.

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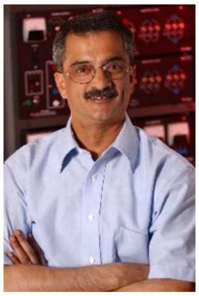
Olga Lavrova is currently a Principal Member of the Technical Staff in the Renewable and Distributed Systems Integration Department at Sandia National Laboratories. Prior to this, Dr. Lavrova was an Assistant Professor in the Electrical and Computer Engineering Department at the University of New Mexico. Dr. Lavrova's research interests include photovoltaics and other emerging renewable energy technologies, as well as nano-scale semiconductor structures and their applications. Being a member of the Power and Energy group at the ECE Department, Dr. Lavrova's research interests include photovoltaics and nano-scale semiconductor structures for photovoltaic applications, as well as Smart Grid and emerging energy generation, distribution and storage technologies. Dr. Lavrova holds a Ph.D. in electrical engineering from the University of California at Santa Barbara, an M.Sc. in electrical engineering A.F. Ioffe Physics Technical Institute, Russia and University College London, and a B.Sc. (Summa Cum Laude) in Physics from the St. Petersburg Electrical Technical University.

Jane Lehr is a professor at the University of New Mexico since 2013 and a Fellow of the IEEE since 2008. Dr. Lehr served as chair of the Electrical and Computer Engineering Department from 2013 to 2015. She is an active researcher in the Applied Electromagnetics Group where the thrust of her research has been studying pulsed power generation and applications and high voltage phenomena. Dr. Lehr served as President of the IEEE Nuclear and Plasma Sciences Society in 2007-2008 and currently serves as the society's Fellow Evaluation Chair. Professor Lehr is the recipient of the 2015 IEEE Nuclear and Plasma Sciences Society's Richard F. Shea Distinguished Member Award.

Chen-Ching Liu is American Electric Power Professor and Director, Power and Energy Center, at Virginia Tech. He was Boeing Distinguished Professor at Washington State University, Pullman, WA. During 1983-2005, he was a Professor of Electrical Engineering at University of Washington, Seattle. Dr. Liu was Palmer Chair Professor at Iowa State University from 2006 to 2008. From 2008-2011, he served as Acting/Deputy Principal of the College of Engineering, Mathematical and Physical Sciences at University College Dublin, Ireland. Professor Liu received an IEEE Third Millennium Medal in 2000 and the Power and Energy Society Outstanding Power Engineering Educator Award in 2004. In 2013, Dr. Liu received a *Doctor Honoris Causa* from Polytechnic University of Bucharest, Romania. Chen-Ching chaired the IEEE Power and Energy Society Fellow Committee, Technical Committee on Power System Analysis, Computing and Economics, and Outstanding Power Engineering Educator Award Committee. He served on the U.S. National Academies Board on Global Science and Technology. Professor Liu is a Fellow of the IEEE and Member of the Washington State Academy of Sciences.

Charles Macal applies computational modeling and simulation tools to complex systems to solve problems in a variety of fields, including energy and national security. He is the chief scientist for the Argonne Resilient Infrastructure Initiative, and is a principal investigator for the development of the widely used Repast agent-based modeling toolkit. He has Appointments at the University of Chicago Computation Institute and the Northwestern-Argonne Institute for Science and Engineering. He is adjunct professor at the University of Chicago, where he teaches a course on Complex Adaptive Systems for Threat Management and Emergency Preparedness. He is a registered professional engineer in the State of Illinois and holds software copyrights for two systems: ELIST (Enhanced Logistics Intra-theater Support Tool) and EMCAS (Electricity Market Complex Adaptive System). He holds a B.S. and M.S. from Purdue University, and a Ph.D. from Northwestern University. He is a member of the Association for Computing Machinery and serves as the Area Editor for Agent-based Modeling for the Transactions on Modeling and Computer Simulation. He is also a member of the Society for Computer Simulation International, and serves as Associate Editor for the Simulation Journal.



Satish Ranade is the PNM Chair Professor in Utility Management and department head of the Klipsch school of Electrical and Computer Engineering, New Mexico State University. He teaches in the Power and Control group and is the Director of the Electric Utility Management Program(EUMP), an entirely industry-funded program that provides MSEE fellowships in the energy area. EUMP graduates hold leadership positions in electric utilities and related industry. His current research is in Renewable Energy Integration and Microgrids. As co-director of the NSF Smartgrid CREST center at NMSU, iCredits, he is involved in research on scheduling and control in renewable rich power systems and in K-12 outreach and interdisciplinary curriculum development. He is past chair of IEEE Power and Energy Society's Career Promotion and Workforce Development Subcommittee.

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Daniel J. Trudnowski received the B.S. degree in engineering science from Montana Tech, Butte, in 1986, and the M.S. and Ph.D. degrees in electrical engineering from Montana State University in 1988 and 1991, respectively. From 1991–1995, he was with Battelle, Pacific Northwest National Laboratory where he was a senior research engineer. In 1995, he joined Montana Tech where he is currently Dean of the School of Mines and Engineering. Prior to this, he was professor and head of the Electrical Engineering Department. His research activities over the past 20 years have primarily focused on problems related to power system dynamics and controls. Dr. Trudnowski is a member of the IEEE Power System and Control System Societies and is a registered professional engineer in the state of Montana. Dr. Trudnowski is a Fellow of the IEEE.

John Undrill holds a B.E. (Hons) and Ph.D. from the University of Canterbury, New Zealand. He is a registered Professional Engineer in the state of New York, a Fellow of the IEEE, and a member of the National Academy of Engineering. John Undrill commenced his professional training in the Electrical Test Room of New Zealand Electricity Department. Dr. Undrill was a Postdoctoral Fellow at the University of Toronto in 1966 and then joined the Electric Utility Engineering Operation of General Electric in Schenectady. He worked at GE until 1970; this period was his professional internship in power system and power plant dynamics. Undrill joined Power Technologies Incorporated in 1972. At PTI he divided his time between engineering and software. He managed the development, marketing and support of the PSS/E grid simulation for most of his 16 years with PTI. He became a Vice President and Director of PTI before departing to join in founding Electric Power Consultants Incorporated in 1986. His professional work at PTI in addition to PSS/E covered a broad range of general dynamics issues including:

- Hydro plant pipeline, tunnel, draft tube, and turbine-governor interactions
- Oil-fired boiler draft controls
- Automatic generation control programs for digital SCADA systems
- Subsynchronous resonance
- Interaction between DC and AC transmission systems

John's work at EPC was the same combination of software and engineering related to power system dynamics. This led to the development of the PSLF grid simulation package. EPC was acquired by General Electric in 1994 and John returned to his former home at GE. At GE he now handed the support of the PSLF program over to others. His principal activity was then in advising and counseling the GE turbine departments on matters relating to the Grid Codes of the many nations where large gas turbines are being commissioned. This involved the development of new analysis, startup work, field testing, and extensive policy-level contact with grid entities in Europe and worldwide. John received the Edison Award of General Electric in 2005 and the Concordia Award of the IEEE in 2006. He was elected to membership of the National Academy of Engineering in 2011. Undrill's experience embraces small isolated power systems like those of New Zealand and Ireland, the major grids of North America and Europe, and systems as varied as those in Brazil, Argentina, Egypt, Turkey, Singapore, and Malaysia. His startup and test experience covers hydro, conventional steam, and combined cycle plants. Dr Undrill was a member of the commission appointed by Bonneville Power Administration to investigate the 1996 breakup of the Western Transmission grid. His transmission grid experience is complemented by work with in-plant generation in the refinery, paper, LNG, and steel industries. John Undrill retired from General Electric in April 2006; he continues to be active in power system and power plant control engineering.

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