IEEE MSC2015 Workshop: Enabling Secure, Scalable Networked Microgrids with High Penetration Renewables and Pulsed Power Loads

This workshop covers technologies for realizing high-performance, agile microgrids. Attendees will be introduced to key challenges in modeling, control, optimization and R&D testing for microgrids capable of operating with high levels of agility and renewable penetration. It is structured as six, self-contained modules. Each module summarizes the current literature, describes challenges and presents current methods for achieving solutions. Opportunities for discussion are available to foster new collaborations and ideation. A workshop specific reference list has been included from which a large portion of the workshop material will draw upon.

The basis of the workshop summarizes a Sandia National Laboratories sponsored three year Grand Challenge Laboratory Directed Research and Development (GC/LDRD) effort. The vision is to develop tools that enable design and trade-off analyses of networked microgrids spanning the space from conventional to 100% stochastic generation. Ongoing projects that apply these tools include NAVSEA Navy all-electric ship Microgrids with pulsed power loads and the ARL (Army Research Laboratories) forward base Microgrid operations.

Energy surety is a matter of national and international security. The present electric grid is based on a foundation created over 100 years ago. The infrastructure is topologically fixed, power sources are centralized and dispatchable (completely controllable), the loads are largely predictable, and the control of power flow at the load is essentially open-loop making it vulnerable to terrorist attacks, natural disasters, infrastructure failures, and other disruptive events. Further, this grid model limits renewables and other distributed energy sources from being economically and reliably integrated into the grid because it has been optimized over decades for large, centralized power generation sources.

Although issues of cost-effective and reliability have long been regarded as fundamental considerations of our present energy infrastructure, in recent years both the Department of Energy (DOE) and the Department of Defense (DoD) have turned attention towards energy surety— providing cost effective supplies of energy that are reliable, safe, secure, and sustainable. However, forward-looking energy surety requires the development of novel intelligent grid architecture in order to be robust, effective, and efficient.

Researchers will leverage capabilities and theories unique to Sandia and MTU, creating advanced models, nonlinear control theory, system control theory, and informatics and flexible experimental hardware testbeds as tools to enable the analysis and design of these complex systems. Ultimately, the goal is to advance and integrate new theories on distributed nonlinear control, agent-based closed-loop controls, informatics, and experimental microgrid hardware testbeds to enable adaptive microgrids and networked microgrids with guaranteed stability and transient performance.

By advancing these sciences and technologies, we are enabling reliable, resilient, secure, and cost-effective microgrids and interconnected microgrids making up the Smart Grid of the future. One of our primary goals of the GC/LDRD is to disseminate technical aspects of the project to the technical community for which the IEEE MSC 2015 workshop provides an ideal setting.

MODULES

Energy Surety Requirements for Microgrid Development

Steven Glover, Sandia National Laboratories, Albuquerque, NM

Rush Robinett III, Michigan Technological University, Houghton, MI

The Secure Scalable Microgrid (SSM) is a Sandia-developed grid architecture that separates away from unidirectional power and limited information flow and, rather, adopts closed-loop controls and an agent-based architecture with integrated communication networks. Adding a feedback component to the input signal establishes an intelligent power flow control and provides a basis for the integration of renewables and distributed power sources into the electrical power grid. This novel approach enables self-healing, self-adapting, self-organizing architecture and allows a trade-off between storage in the grid and information flow to control generation sources, power distribution, and loads.

The SSM consists of a multilayer feedback control system. This new approach includes agent-based, closed loop architecture of the entire system with two main levels. The high-level layer, agent-based informatics architecture, regulates the mixture of energy resources, performs load leveling and prioritization and allows adaptive behavior. Basically, it chooses the network topology connecting the power generators, energy storage, and distribution/ transmission lines in order to service the loads within the SSM while optimizing the SSM priorities.

The low-level layer, distributed nonlinear control, ensures and maintains stability and transient performance of the network topology chosen by the high-level layer of the SSM. The interplay of these two levels is critical for the success of new control and informatics driven electric power grid. Specifically, the top-level layer must be effective and efficient in the selection process while the low level layer must guarantee stability and performance for non-linear systems.

Incorporating agent-based, distributed, nonlinear control to maintain reliable energy distribution while minimizing the need for excessive storage or backup generation will be a revolutionary step towards extreme penetration of renewable energy sources into the U.S. energy infrastructure. The development of dynamic nonlinear source models, scalable agent-based architectures and multi-time-variant simulations will be key components to this solution.

Microgrid Modeling using MATLAB/Simulink: Components-to-Systems

Wayne Weaver, Michigan Technological University, Houghton, MI

Power electronics have been an enabling technology to increase the diversity, flexibility and controllability of energy sources and loads in modern electric power systems and microgrids. In fact, power electronics are a central technology for microgrids because there are very few modern electrical loads or energy storage components that do not have a power electronic interface. In addition, more and more energy sources including renewables such as wind and solar need to have power electronics to interface to the grid.

Therefore, modeling and simulation of these components is a vital step in the hardware architecture and control system design cycle.

Basic circuits of building power electronic building blocks for ac-dc, dc-dc, and dc-ac conversion will be presented. Then, the state-space representations of switching and average-mode conversion processes and components will be covered. Finally, the component building blocks will be assembled into systems-of-systems models of microgrids in the MATLAB/Simulink modeling environment. The basics of droop and load sharing control methods will also be presented. These rudimentary load sharing methods will be used as the mechanism for optimization and higher level system level controls.

Microgrid Optimal Control and Optimization

Gordon Parker, Michigan Technological University, Houghton, MI

Energy storage capacity and management heavily influence agile microgrid performance. This provides opportunities for both optimal control and optimization. Using a very simple microgrid analogy, the benefit of nonlinear, optimal control is illustrated. Extension of this approach to larger more complex microgrid architectures will be presented. Optimization is explored at multiple levels. A high-level, PEV agent strategy is introduced for reducing power consumption peaks. This is contrasted with a low level storage system design method based on extremizing power converter control strategies.

Microgrid Agent-Based Control for Mediating Generation, Storage, Loads, Cyber Security

Marvin Cook, Sandia National Laboratories, Albuquerque, NM

Steven Y. Goldsmith, Michigan Technological University, Houghton, MI

This module will introduce a distributed control system for autonomous, agile microgrids that is based on a multi-agent system (MAS) architecture. The MAS architecture relies on a hybrid design approach that integrates a continuous time-varying state-space model with a distributed discrete event model. Using a DC bus composed of various sources and loads connected through DC-DC converters as an example, the system and agent models will be developed followed by a the design of a few agent-agent interaction protocols that implement a model-based cooperative control scheme. The module will conclude with the demonstration of a hybrid simulator that illustrates some of the important design and performance issues surrounding agent task allocation, communications latency, and computation times for the control law and optimization functions.

Microgrid Control and Performance Analysis

David Wilson, Sandia National Laboratories, Albuquerque, NM

An innovative control system design process, the Hamiltonian Surface Shaping and Power Flow Control (HSSPFC), is specifically suited for high penetration of renewable generation microgrid systems as critical components associated with the future smart grid. The HSSPFC design methodology is the outcome of combining concepts from thermodynamic exergy and entropy; Hamiltonian systems; Lyapunov's direct method and Lyapunov optimal analysis; static and dynamic stability analysis, electric AC power concepts including limit cycles; and power flow analysis. Several representative AC/DC microgrid control and performance analysis examples (high penetration renewable energy, NAVSEA all electric ship microgrids) will be explored during this workshop.

Sandia National Lab's Secure Scalable Microgrid Testbed: Capabilities and Collaboration

Jason Neely and Steven Glover, Sandia National Laboratories, Albuquerque, NM

Sandia National Laboratories is expanding their renewable energy research to develop new tools for the design and analysis of power systems with high penetration levels of stochastic renewable sources. A necessary step for this research is experimental validation, which has resulted in the development of a hardware testbed called the Secure Scalable Microgrid Testbed (SSMTB). Given a time-indexed load and weather profile that includes load resistances (Watts or Ω), wind speed (m/sec), wave crest (m), river currents (m/sec), solar irradiance (W/m^2), etc.), the testbed can be used to repeat an experiment over and over using different control schemes but the same simulated test conditions. This is done from a central computer interface.

PRELIMINARY SCHEDULE

8:00	Energy Surety Requirements for Microgrid Development
8:50	Break
9:05	Microgrid Modeling using MATLAB/Simulink: Components-to-Systems
10:05	Break
10:20	Microgrid Optimal Control and Optimization
11:20	Lunch
12:20	Microgrid Agent-Based Control for Mediating Generation, Storage, Loads, Cyber Security
1:20	Break
1:35	Microgrid Control and Performance Analysis
2:35	Break
2:50	Sandia National Lab's Secure Scalable Microgrid Testbed: Capabilities and Collaboration
3:50	Wrap-up

INSTRUCTOR BIOGRAPHIES

Steven Glover, Manager, Sandia National Laboratories, Albuquerque, NM

Dr. Glover obtained his B.S. and M.S. degrees in electrical engineering from the University of Missouri-Rolla, Rolla, Missouri, in 1995 and 1997, and the Ph.D. degree with research on modeling and stability analysis of power electronics based systems from Purdue University, West Lafayette, Indiana, in 2003. He was a Research Engineer for P.C. Krause and Associates from 1996 to 2001 where he created simulations, performed model validation, and provided support for integrated power systems. From 1997 to 1998 he served as an Associate Research Engineer with the University of Missouri-Rolla and then as a Research Engineer at Purdue University until 2003, pursuing interests in power electronics based systems. In May 2003 he joined Sandia National Laboratories, Albuquerque, NM, where he is the Manager of the Advanced Pulsed Power Systems Department which performs research spanning from materials to systems. Current research includes developing design and analysis techniques for

Microgrids and renewable energy systems through the integration of informatics, nonlinear distributed control, communications, and hardware.

Rush D. Robinett III, Richard and Elizabeth Henes Professor, Mechanical Engineer, Michigan Tech
Dr. Robinett has three degrees in Aerospace Engineering from Texas A&M University (B.S. - 1982, Ph.D. - 1987) and The University of Texas at Austin (M.S. - 1984). He has authored over 100 technical articles including three books and holds 8 patents. Rush began his career at Sandia National Laboratories in 1988 as a Member of the Technical Staff working on the Star Wars Program (Ballistic Missile Defense). In 1995, he was promoted to Distinguished Member of Technical Staff. In 1996, he was promoted to technical manager of the Intelligent Systems Sensors and Controls Department within the Robotics Center. In 2002, Rush was promoted to Deputy Director and Senior Manager of the Energy and Infrastructure Future Group where he is developing new opportunities in distributed, decentralized energy and transportation infrastructures with a focus on entropy and information metrics. Presently, he is professor at Michigan Technological University, ME-EM Department.

Wayne Weaver, Associate Professor Electrical Engineering, Michigan Tech
Dr. Weaver's area of expertise is in the areas of power electronics and microgrids. His research focus is in distributed control methodologies in microgrids that enable robust and efficient distribution of energy resources. Prior to his current position he worked as a control system development engineer in the electric power generation group at Caterpillar Inc, and as a research associate at the U.S. Army Corp of Engineers - Construction Engineering Research Lab in the area of military microgrids.

Gordon G. Parker, John and Cathi Drake Professor of Mechanical Engineering, Michigan Tech
Dr. Parker has been developing control strategies for electro-mechanical systems for the past 24 years. He and his graduate students recently developed a mobile microgrid research and education laboratory through a grant sponsored by the U.S. DOE. This will be used to compliment previous studies in electric vehicle / grid interaction. Navy logistics operations, diesel engine aftertreatment state estimation and wind turbine modeling and control are other active research areas. The research conducted by Dr. Parker and his students has resulted in more than 115 peer-reviewed articles and 40 graduate student theses. Prior to taking his current position at Michigan Tech he spent four years at Sandia National Laboratories in Albuquerque developing a variety of structural vibration control solutions including large-angle spacecraft reorientation.

Marvin Cook, R&D Software Engineer, Sandia National Laboratories, Albuquerque, NM

Mr. Cook received a BS in Computer Science from the University of South Florida and MS in Computer Science from Johns Hopkins University in 1999 and 2000 respectively. He is a R&D software engineer for the Military & Energy Systems Analysis Department at Sandia National Laboratories. During his 13 years at Sandia, he has developed several multi-agent oriented systems with an emphasis on situated reasoning and cyber security. Currently, he is designing and implementing an agent oriented approach to achieve high penetration of renewables and microgrid connectivity.

Steven Y. Goldsmith, Research Professor Mechanical and Electrical Engineering, Michigan Tech
Dr. Goldsmith is a currently a Research Professor at Michigan Technological University with dual appointments in the Mechanical Engineering and Engineering Mechanics Department, and the Electrical and Computer Engineering Department. He is also a Senior Fellow at the Technological Leadership Institute at the University of Minnesota. Dr. Goldsmith spent 32 years with Sandia National Laboratories and retired as Distinguished Member of the Technical Staff in 2011. His current research efforts are focused on intelligent agent systems and technology, particularly the development of adaptive and multi-

agent systems. His current projects involve the application of intelligent agents to "smart" electric grid controls, automated cyber defense, and complex energy systems management.

David G.Wilson, R&D Control Engineer, Sandia National Laboratories, Albuquerque, NM
Dr. Wilson has three degrees in Mechanical Engineering (BS, MS, PhD). He has authored over 50 technical articles that include three books. He is the R&D nonlinear controls lead for the Electrical Science and Experiments Department at Sandia National Labs. He has over 25 years of research and development engineering experience in energy systems, robotics, automation, and space and defense projects. His areas of research include nonlinear/adaptive control, distributed decentralized control, and exergy/entropy control for nonlinear dynamical systems. Currently he is developing nonlinear power flow control systems for critical energy surety microgrid systems. He is the current PI on the NAVSEA future electric ship nonlinear controls and power systems for advanced microgrid design project.

Jason Neely, R&D Electrical Engineer, Sandia National Laboratories, Albuquerque, NM

Dr. Neely received BS and MS degrees in Electrical Engineering from the University of Missouri-Rolla (now the Missouri School of Science and Technology, Missouri S&T) in 1999 and 2001 respectively and a Ph.D in Electrical Engineering from Purdue University in 2010. Jason currently has 16 technical publications; Jason's interests include machine and drive systems, electrical generation, power electronics, and optimal control. Jason joined Sandia National Labs in Albuquerque, NM in 2001; he currently works in the Advanced Pulsed Power Systems Department.

Previous Conducted Nonlinear Controls IEEE Workshops, mini-courses and tutorial:

Robinett III, R.D., Wilson, D.G., and Parker, G.G., *Nonlinear Power Flow Control Design: Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis and Optimization*, Tutorial, IECON 2011, Crown Conference Centre, Melbourne, Australia, November 7, 2011.

Robinett III, R.D. and Wilson, D.G., *Nonlinear Power Flow Control Design: Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis*, Workshop, 2011 IEEE Multi-Conference on Systems and Control, Denver, CO, September 27, 2011.

Robinett III, R.D. and Wilson, D.G., *Nonlinear Power Flow Control Design: Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis*, University of Padova, Padova, Italy, Invited Workshop / Mini-Course, July 18-22, 2011.

Robinett III, R.D. and Wilson, D.G., *Nonlinear Power Flow Control Design: Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis*, 47th IEEE Conference on Decision and Control Workshop, Cancun, Mexico, Dec. 8th, 2008. ONLINE Slide Presentation Material: http://energy.sandia.gov/?page_id=3057#Nonlinear

IEEE MSC Workshop Topic Specific References:

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Robinett III, R.D., Wilson, D.G., and Goldsmith, S.Y., *Collective Control of Networked Microgrids with High Penetration of Variable Resources Part I: Theory*, IEEE-Cyber 2012 Conference, Imperial Queen's Park Hotel, Bangkok, Thailand, May 27-31,2012.

Neely, J., Pekarek, S., Glover, S, Finn, J., Wasynczuk, O. and Loop, B., An Economical Diesel Engine Emulator for Micro-grid Research, *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, SPEEDAM 2012, June 20-22, Sorrento, Italy.

Bordeau, K., Parker, G., Vosters, G., Weaver, W., Kelly, J., Wilson, D.G., Robinett III, R.D., Distributed Control of Plug-in Hybrid Electric Vehicles on a Smart Grid, *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, SPEEDAM 2012, June 20-22, Sorrento, Italy.

Heath, M., Vosters, G., Parker, Weaver, W., Wilson, D.G., Robinett III, R.D., DC Microgrid Optimal Storage Distribution Using a Conductance and Energy State Modeling Approach, *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, SPEEDAM 2012, June 20-22, Sorrento, Italy.

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Robinett III, R.D. and Wilson, D.G., **Nonlinear Power Flow Control Design: Utilizing Exergy, Entropy, Static and Dynamic Stability, and Lyapunov Analysis,** Springer-Verlag London Ltd., August 2011, ISBN 978-0-85729-822-5.

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Robinett III, R.D. and Wilson, D.G., *Collective Plume Tracing: A Minimal Information Approach to Collective Control*, Published online in Wiley Interscience (www.interscience.wiley.com). DOI: 10.1002/rnc.1420, March 27, 2009.

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Schenkman, B.L., Wilson, D.G., Robinett III, R.D. and Kukolich, K., *Photovoltaic Distributed Generation for Lanai Power Grid Real-time Simulation and Control Integration Scenario*, International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2010, June 14-16, Pisa, Italy.