UILU-ENG-2020-2501

# FORTY-FIRST ANNUAL REPORT
# OF THE
# POWER AFFILIATES PROGRAM

University of Illinois at Urbana-Champaign
Department of Electrical and Computer Engineering
306 N. Wright St.
Urbana, IL 61801

PAP-TR-20-01

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# FOREWORD

This report provides a summary of Power Affiliates Program (PAP) activities in the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign for the calendar year 2019. Information listed below is intended to be a progress report to the affiliate companies. The PAP is the foundation of the industrial liaison effort in the power and energy systems area. Current affiliates associated with the PAP are:

Ameren
City Water, Light & Power, Springfield, IL
Continental Automotive
Electrical Manufacturing & Coil Winding Association, Inc.
Exelon
Flanders Electric
G&W Electric
MidAmerican Energy Company
PowerWorld Corporation
S&C Electric Company
Sargent & Lundy Engineers
Professor Emeritus M. A. Pai

2019 was an active year for the PAP and the highlights are covered in this report. We acknowledge the valuable interaction of the Affiliates and are most thankful to these companies for their continued support.

Peter Sauer, Director
Robin Smith
Joyce Mast
Arijit Banerjee
Subhonmesh Bose
Kevin Colravy
Alejandro Domínguez-García
George Gross
Kiruba Haran
Philip Krein
Andrew Stillwell
Richard Zhang

# 1. INTRODUCTION AND SUMMARY

The Power Affiliates Program was initiated in January 1979 as part of a major effort to strengthen the power and energy systems area. The original objectives were to:

- Maintain stimulating, meaningful and high quality undergraduate and graduate programs in electric power engineering.
- Increase university-industrial interaction at all levels of education and research in electric power engineering.

These objectives are as valid today as they were in 1979. The multi-faceted activities in 2019 under the PAP umbrella clearly were in support of these objectives.

Throughout the past 41 years, the PAP has maintained a stable financial base during times of rapid change in the power industry and provided seed money for research. This led to additional funding by other sources and has made it possible for students to be exposed to industrial problems and participate in technical and professional meetings. Given the cyclical nature of funding by government agencies, the PAP is a critically important source of support.

This annual report is organized as follows. The financial statement for the 2019 calendar year is given in Section 2. Section 3 describes how the Power Program fits into the departmental structure. There is no official degree or option associated with the Power Program, but there is a significant level of specialization, which is possible through a set of courses developed and offered by the faculty group who constitute the Power and Energy Systems Area. Section 4 gives a brief description of the courses for specializing in electric power and tabulates the enrollment figures for the most recent offerings. Included in this section is a historical record of the number of graduates who have taken three or more of these courses. Section 5 lists the activities of both the students and the faculty members during the 2019 calendar year. Section 6 gives information about the graduate students in the power area. In addition to personal data and interests, each student has written a brief abstract of his or her research work. Laboratories and other facilities of the power area are discussed in Section 7. The report concludes with a directory in Section 8 and in Section 9 with the 2019 publications list.

## 2. FINANCIAL STATEMENT

The following tabulation of income and expenditures for the calendar year 2019 was prepared from a detailed University statement as of December 31, 2019.

| | |
|---|---|
| Income carried over from the 2018 calendar year | $76,224 |
| Total income during Calendar Year 2019 * | $ 47,971 |
| Total available income during calendar year 2019 | $ 124,195 |

| **Expenditure** | **Expenditure Amount** |
|---|---|
| Personnel | $ 42,476 |
| Supplies | $ 857 |
| Transportation/Travel/Services | $ 24,230 |
| Total expenditures | $ 67,563 |

**Summary**

| | |
|---|---|
| Amount of funds available during calendar year 2019 | $ 124,195 |
| Amount of expenses during calendar year 2019 | $ 67,563 |
| Balance as of December 31, 2019 | $ 56,632 |

* This does not include funds that were received in 2019 but not posted on the university accounting system until 2020.

## 3. THE POWER PROGRAM WITHIN THE DEPARTMENT

Electrical engineering undergraduate students are required to complete 128 hours of course work for a BSEE degree. Detailed descriptions of the undergraduate program and suggested curriculum in Power are on the Department web site. The MEng is a technical degree requiring a minimum of 32 credit hours and includes a professional development requirement. MSEE students are required to complete a minimum of 32 credit hours including a graduate thesis. All PhD students must qualify through a research paper and presentation and complete course and thesis requirements. A detailed description of the graduate programs is given on the Department web site.

The Electrical and Computer Engineering Department is subdivided into eight distinct technical areas as follows:

Biomedical Imaging, Bioengineering, and Acoustics

Circuits and Signal Processing

Communications and Control

Computer Engineering

Electromagnetics, Optics and Remote Sensing

Microelectronics and Photonics

Nanotechnology

Power and Energy Systems

While the Department does not have official degree-granting options in these areas, in practice, the eight areas serve as the appropriate grouping of faculty activities and interest. In terms of size, the Power and Energy Systems area represents about 9% of the total active faculty and about 14% of the total student enrollment. The faculty committee in each group has the responsibility for administering courses and research in that group within the Department. The Power and Energy Systems Area Committee and associated faculty for the 2019 – 2020 year together with their fields of interest are:

| | |
|---|---|
| A. Banerjee | Electromechanical energy conversion systems, power electronics, electrical machines and drives, electric propulsion systems, renewable energy, robotic actuators |
| S. Bose | Algorithm and market design for power systems, renewable integration, smart transportation, networked dynamical systems |
| A. Domínguez-García | Power and energy systems, microgrids, grid data analytics, reliability analysis, cyberinfrastructures, decision science |
| G. Gross | Large-scale system analysis and computing, energy economics, electricity markets, effective bio-fuel applications for electricity, electricity planning and analysis, storage and renewable resource integration, electric vehicles |
| K. Haran | Autonomous vehicular technology, unmanned aerial vehicles, electric transportation, electrical machines and drive systems, power and energy systems |

| | |
|---|---|
| P. T. Krein (Emeritus) | Electric machinery and electromechanics, power and energy systems, power electronics, energy efficient buildings, transportation electrification |
| P. W. Sauer (Emeritus) | Electrical machines and drive systems, power and energy systems, cyber security of power system energy management systems, power system stability, dynamic modeling and simulation |
| A. Stillwell | Power electronics, alternative and renewable energy systems, transportation electrification, wide bandgap power devices, design optimization |
| R. Zhang | Electric power systems, large-scale algorithms, stability analysis, data analytics, mathematical optimization, machine learning |

Two of the primary responsibilities of the Power and Energy Systems Area Committee are to improve, keep current, and staff the courses assigned to the Power and Energy Systems Area. In 2019 those courses were:

| | |
|---|---|
| ECE 298 AB | Solar Car |
| ECE 307 | Techniques for Engineering Decisions |
| ECE 313 | Probability with Engineering Applications |
| ECE 330 | Power Circuits and Electromechanics |
| ECE 333 | Green Electric Energy |
| ECE 431 | Electric Machinery |
| ECE 432 | Advanced Electric Machinery |
| ECE 464 | Power Electronics |
| ECE 469 | Power Electronics Laboratory |
| ECE 476 | Power System Analysis |
| ENG 491 | Interdisciplinary Design Courses |
| ECE 530 | Analysis Techniques for Large-Scale Electrical Systems |
| ECE 554 | Dynamic System Reliability |
| ECE 568 | Modeling and Control of Electromechanical Systems |
| ECE 573 | Power Systems Operations and Control |
| ECE 576 | Power System Dynamics and Stability |
| ECE 588 | Electricity Resource Planning |
| ECE 590 I | Seminar: Power Systems |
| ECE 598 AB | Power-Electronic Converter and Control for Electric Machines: Theory and Practice |
| ECE 598 SB1 | Electricity Markets |

The four-hundred level courses are advanced undergraduate or beginning graduate courses, while the five-hundred level are graduate courses. The Power and Energy Systems Area Committee periodically evaluates each course outline for possible revision for future offerings. A brief description of each of these courses, together with the enrollment of the past year, is included in the next section. In addition, the Power Faculty supervises numerous student projects performed in ECE 445. This is the capstone design course for our seniors.

## 4. COURSES AND ENROLLMENT

As one of eleven featured research areas and one of five cross-cutting themes in Electrical and Computer Engineering, the Power and Energy Systems Area is responsible for the development and offering of a substantial number of courses. Current courses assigned to our area are described briefly below. Total enrollment for courses offered in the 2019 - 2020 academic year is also given for each course.

**ECE 298 AB: Solar Car**

The course objective is to show students that a multidisciplinary understanding is essential to create a complex system. UIUC's own Solar Car "Argo" is the example. The course covers high-level aspects of the design, construction, analysis, and economics of solar-powered electric vehicles. Topics bridge a variety of engineering disciplines integrated with business to present an overview highlighting complexities of solar-powered vehicles. Students are expected to gain hands-on experience working with the Solar Car Team to build the next solar car. In-class presentations provide a platform for individuals to convey ideas and contributions to a broad set of multidisciplinary audience. In place of a text are Instructor Notes and *Solar Car Wiki*. References are *Solar Car Primer*, by E. F. Thacher and *The Leading Edge: Aerodynamic Design of Ultra-Streamlined Land Vehicles*, by G. Tamai, 1999. The total enrollment for academic year 2019 - 2020 was 16.

**ECE 307: Techniques for Engineering Decisions**

This three-hour course is concerned with modeling decisions and modeling analysis of models to develop a systematic approach to making decisions. The focus is on developing techniques for solving typical problems faced in making engineering decisions in industry and government. Topics include resource allocation, logistics, scheduling, sequential decision making, siting of facilities, investment decisions and other problems for decision making under uncertainty. Extensive use of case studies gets students involved in real-world decisions. The course has two required texts: *Operations Research: Principles and Practice*, by A. Ravindran, D. T. Phillips and S. S. Solberg and *Making Hard Decisions: An Introduction to Decision Analysis*, by R. T. Clemen. This class was not offered in the 2019 - 2020 academic year..

**ECE 330: Power Circuits and Electromechanics**

The goal of this three-hour course is to provide an introduction to three-phase circuits, transformers, and electromechanical systems with an emphasis on analysis and some design insight. The course starts with a review of phasors followed by three-phase power circuits, mutual inductance, magnetic circuits and transformers. Electromechanical systems are analyzed using energy-balance concepts. Introduction to synchronous, induction, dc and small machines is given. The required text is *Power Circuits and Electromechanics*, by M. A. Pai. The total enrollment for the academic year 2019 - 2020 was 238.

**ECE 333: Green Electric Energy**

A course on the challenges of meeting future energy needs using renewable resources; this is a three-hour technical elective for engineering introductory-level undergraduate students with a background in electric circuits. The course explores the technical, economic, environmental and policy aspects of renewable and alternative energy systems to provide a comprehensive picture of their role in meeting society's electricity needs. The upsurge in the worldwide demand for oil-based resources, the restructuring of the electricity industry, advances in engineering technology and the increasing interest in environmental protection are presenting unparalleled challenges to the electric power industry. The role of new energy-resource technologies, the application of power electronics, the use of demand-side management, and the effects of market forces in addressing these challenges are discussed. The course covers the basics of energy production from renewable sources, the relevant thermodynamics background, the structure and nature of the interconnected electric power system and the critical need for environmentally sensitive solutions. In addition, the economic and regulatory policy aspects of electricity and electricity markets are treated. The course has the following texts: *Renewable and Efficient Electric Power Systems*, 2nd Edition, by G. M. Masters, plus additional lecture material, homework problems (solutions) and other resources posted at http://courses.engr.illinois.edu/ece333/. The total enrollment for academic year 2019 - 2020 was 143.

**ECE 431: Electric Machinery**

This four-hour course contains a laboratory one-credit hour component, which is an elective in a list of fourteen from which students select two. The fifteen experiments typically include power measurement, power-factor correction, transformer characteristics, three-phase transformer connections, induction motor tests, induction motor torque-speed characteristics, synchronous machine tests, synchronous-machine power characteristics, digital simulation of machine dynamics, motor control, and a written and oral project presentation on power and energy system topics. The required text is *Electric Machinery,* by Fitzgerald, Kingsley, and Umans. The total enrollment for academic year 2019 - 2020 was 54.

**ECE 432: Advanced Electric Machinery**

This three-hour course contains advanced theory and analysis of rotating and linear machines and drives. It includes power electronic drives for dc and ac motors. The analysis uses *d-q* transformations and related techniques. Emphasis is placed on time-scale modeling of electromechanical devices and on their function in drives. The required text was *Analysis of Electric Machinery and Drive Systems*, by P. C. Krause, O. Wasynczuk and S. D. Sudhoff, IEEE Press. This class was not offered in the 2019 - 2020 academic year.

**ECE 464: Power Electronics**

This three-hour course is a comprehensive treatment of switching power-conversion systems and the devices used to build them. Concepts of switch control are developed from general switching functions. Phase control, pulse-width modulation, and phase modulation are studied for applications in all types of converters. Converter topologies are introduced along with design concepts for power filters and interfaces. Devices such as diodes, thyristors, bipolar transistors, field-effect transistors, capacitors, and magnetic components are examined in the context of high-power switching applications. The required text is *Elements of Power Electronics*, 2nd Edition, by P. T. Krein. The total enrollment for academic year 2019 - 2020 was 81.

**ECE 469: Power Electronics Laboratory**

This two-hour course, designed to accompany ECE 464, is a laboratory study of circuits and devices used for switching power converters, solid-state motor drives, and power controllers, including dc-dc, ac-dc, and dc-ac converters and applications. It includes high-power measurements for silicon-controlled rectifiers, diodes, capacitors, power transistors and magnetic components. A lab manual by P. T. Krein is used for this course. The total enrollment for the academic year 2019 - 2020 was 43.

**ECE 476: Power System Analysis**

This three-hour course is the first of two courses on power system analysis. Topics included are transmission-line parameter calculations, equivalent circuits, network analysis, load flow, fault analysis, symmetrical components, unsymmetrical fault analysis, and introduction to economic dispatch. The course is designed to be a stand-alone introduction to the fundamentals of power system analysis and provide the basis for all subsequent courses in power system analysis. The required text is *Power System Analysis & Design*, 6th Edition, by J. D. Glover, T. J. Overbye and M. S. Sarma. The total enrollment for academic year 2019 - 2020 was 33.

## GRADUATE COURSES:

### ECE 530: Analysis Techniques for Large-Scale Electrical Systems

This is a four-hour course in modeling power systems in steady-state and dynamic regimes. It includes analysis and simulation techniques for power and power electronics systems as well as computational issues in power systems and power electronics. Topics covered are advanced power flow, sparsity techniques, power-flow control, least-squares and estimation-applications averaging techniques for power electronics systems, numerical integration of differential equations and Krylov subspace applications. The course uses notes by George Gross in lieu of a text. The total enrollment for academic year 2019 - 2020 was 15.

### ECE 554: Dynamic System Reliability

This four-hour course offers subjects in new and developing areas of knowledge in electrical and computer engineering intended to augment the existing curriculum. Topics include basic reliability concepts, uncertainty modeling, reliability analysis, system design, fault detection, diagnosis, and applications. Texts are *System Reliability Theory*, by M. Rausand and A. Hoyland, *Uncertain Dynamic Systems*, by F. Schweppe, *Mathematical Theory of Reliability*, by R. Barlow and F. Proschan, and *Fault-Diagnosis Systems*, by R. Isermann. This class was not offered in the 2019 - 2020 academic year.

### ECE 568: Modeling and Control of Electromechanical Systems

This four-hour course addresses issues of electrical drives in a modern control and circuit framework. Dynamic models of electric machines are presented. There is special emphasis on field-oriented control methods for ac motors. Power electronics systems for high-performance drives are studied. Nonlinear system methods such as periodic transformations, averaging, geometric control, and feedback linearization are presented. Special topics covered include electrostatic micromachines and permanent magnet machines. The recommended texts are *Control of Electrical Drives*, 2nd edition, by W. Leonard and *Analysis of Electric Machines*, 2nd edition by P. Krause, O. Wasynczuk and S. Sudhoff. This class was not offered in the 2019 - 2020 academic year.

### ECE 573: Power Systems Operations and Control

This four-hour course provides an overview of power system operations and control with major emphasis on security and economics. The role of EMS (energy management system) and principal EMS functions are discussed in depth. Major topics include: optimal power flows; economic dispatch problems; role of reactive power; resource scheduling and commitment; state estimation; observability; bad data identification/detection, analysis and processing; electricity restructuring; competitive electricity markets; market design; congestion management; and ancillary services. The two suggested texts are

*Power Generation, Operation and Control*, 2nd edition, by Wood and Wollenberg, and *State Estimation in Electric Power Systems: A Generalized Approach* by A. Monticelli, Kluwer Academic Publishers, Boston, 1999. This class was not offered in the 2019 - 2020 academic year.

**ECE 576: Power Systems Dynamics and Stability**

This four-hour course includes the dynamic representation of interconnected power systems — electrical plus mechanical, linearized dynamic models of multi-machine systems, methods of coherency identification, order reduction by singular perturbation, time-scale decomposition and aggregation techniques, dynamic equivalents, direct methods of stability analysis and power system stabilizer design. The required text is *Power Systems Dynamics and Stability* by P. W. Sauer and M. A. Pai. The total enrollment for academic year 2019 - 2020 was 8.

**ECE 588: Electricity Resource Planning**

This four-hour course provides coverage of the basic techniques in electricity resource planning including methodologies for reliability evaluation and assessment, production costing, marginal costing, supply-side and demand-side planning and integrated resource planning. Throughout the course, probabilistic approaches are emphasized. In place of a text, notes specifically prepared by George Gross are used. This class was not offered in the 2019 - 2020 academic year.

**ECE 590 I Seminar: Power Systems**

This course is a graduate seminar on advanced topics of current interest. Both faculty and students participate by presenting either current research results or topics of interest in journal publications. Guest speakers from industry and other universities are also scheduled periodically throughout the semester. Approximately 54 students participated in this course for both semesters.

**ECE 598 KSH: Electrical Machine Design**

Technologies like advanced materials, manufacturing processes and power electronics can open up the design space for new electrical machine solutions aimed at emerging applications in the transportation, energy, and industrial sectors. To take full advantage of these developments, engineers need to be well versed in the multidisciplinary design process for electrical machines, with a good understanding of complex trade-offs that span multiple disciplines. They must also be comfortable with both analytical and numerical tools and know when to apply these to obtain the best results. The course attempts to prepare electrical and mechanical engineers for this opportunity by focusing on practical design considerations. It builds on fundamentals covered in ECE 330 and 431 and takes students through the design of a variety of electromechanical devices. Fundamental principles of energy conversion applicable to all types of electric machinery are first reviewed. Basic design rules, analytical formulae and the use of numerical design tools are then introduced, and experience is gained through a hands-on design project. This class was not offered in the 2019 - 2020 academic year.

**ECE 598 AB: Power-Electronic Converter and Control for Electric Machines: Theory and Practice**

This course introduces modeling, analysis, and design of electromechanical energy-conversion systems from a simultaneous perspective of power electronics, electromechanics, and control. We will take a hands-on approach. Theories are discussed in lectures and implemented in real-world laboratory setups. Three-phase power-electronic converters specifically designed for machine drives are introduced. Dynamic models of different types of electrical machines are developed using generalized machine theory. Finally, different control architectures and their impact on the dynamic performance of the drive are discussed. "Real-world" examples from many existing and emerging applications including electric vehicles, renewable energy systems, and high-power and high-performance industrial drives are used to show the need for interdisciplinary understanding from a system perspective. The required text is *Control of Electrical Drives* by W. Leonhard. References include *Vector Control and Dynamics of AC Drives* by D. W. Novotny and T. A. Lipo, *High-Power Converters and AC Drives* by B. Wu and M. Narimani, *Control of Electric Machine Drive Systems* by S. Sul, *Power Electronics and Motor Drives: Advances and Trends* by B. K. Bose and various IEEE papers. Prerequisites: ECE 464 (Power Electronics) and ECE 431 (Electric Machinery). ECE 486 is preferred. The total enrollment for academic year 2019 - 2020 was 24.

**ECE 598 SB1: Mathematical Foundations of Electricity Markets**

Power system operation is linked to the operation of electricity markets. In this course, we study the modeling and analysis of competitive electricity markets that facilitate the balance of demand and supply of electricity across a power network. We leverage tools from optimization theory, microeconomics, and game theory to investigate the rationale behind current market designs, how they operate, and analyze the outcomes, given the strategic behavior of the market participants. The course illustrates the complex interaction of mechanism design with the physics of the underlying grid, a feature that distinguishes electricity markets from traditional marketplaces. While the bulk of the course focuses on wholesale electricity markets in the US, we conclude with current debates on the creation of retail markets to harness the flexibility of demand-side resources. The total enrollment for academic year 2019 - 2020 was 13.

**NUMBER OF ELECTRIC POWER AND ENERGY SYSTEM AREA GRADUATES IN RECENT YEARS**

Annual Average Power Area Graduates

1950-1970

| | | |
|---|---|---|
| B.S.E.E. | - | 25 |
| M.S.E.E. | - | 3 |

1970-1980

| | | |
|---|---|---|
| B.S.E.E. | - | 44 |
| M.S.E.E. | - | 7 |

1980-1990

| | | |
|---|---|---|
| B.S.E.E. | - | 32 |
| M.S.E.E. | - | 5 |
| Ph.D. | - | 2 |

1990-1995

| | | |
|---|---|---|
| B.S.E.E. | - | 40 |
| M.S.E.E. | - | 6 |
| Ph.D. | - | 2 |

1995-2000

| | | |
|---|---|---|
| B.S.E.E. | - | 35 |
| M.S.E.E. | - | 9 |
| Ph.D. | - | 3 |

2000-2005

| | | |
|---|---|---|
| B.S.E.E. | - | 40 |
| M.S.E.E. | - | 8 |
| Ph.D. | - | 3 |

2005-2010

| | | |
|---|---|---|
| B.S.E.E. | - | 50 |
| M.S.E.E. | - | 10 |
| Ph.D. | - | 5 |

2010-2015

| | | |
|---|---|---|
| B.S.E.E. | - | 60 |
| M.S.E.E. | - | 12 |
| Ph.D. | - | 6 |

2015-2020

| | | |
|---|---|---|
| B.S.E.E. | - | 67 |
| M.S.E.E. | - | 14 |
| Ph.D. | - | 7 |

## 5. ACTIVITIES

Faculty and students in the Power and Energy Systems Area participated in a considerable number of special activities during the calendar year 2019. The major events are listed below:

JANUARY

- Kiruba Haran attended the American Institute of Aeronautics and Astronautics (AIAA) SCITECH Forum in San Diego, CA.
- Arijit Banerjee gave an invited talk at the Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) for Industry Day in Washington, DC.
- Kiruba Haran visited Johnson Controls International (JCI) in New Freedom, PA.
- Philip Krein visited Berkeley and Stanford, CA for the Zhejiang University/ University of Illinois Institute.
- Philip Krein visited Madison, WI for the Zhejiang University/University of Illinois Institute.

FEBRUARY

- Arijit Banerjee attended the 2019 Solar Car Conference at Southern Illinois University Edwardsville (SIUE) in the St. Louis area.
- Philip Krein participated as a judge at IEEE Empowering a Million Lives Competition and served as a panelist at the IEEE Decentralized Energy Access Solutions (DEAS) Workshop in Atlanta, GA.
- Philip Krein served as Executive Dean at the Zhejiang University/University of Illinois at Urbana-Champaign Institute in China.
- Philip Krein presented an invited talk at the University of Nottingham – Ningbo in China.
- George Gross was invited by the Science Foundation Ireland (SFI) to serve on as a member of the panel to evaluate the SFI Centre for Marine Renewable Energy Research progress on its performance at its site in University College Cork, Ireland.
- Alejandro Domínguez-García attended the Network Optimized Distributed Energy Systems (NODES) Program Annual Review Meeting in Pasadena, CA.
- George Gross gave an invited talk at the MCA (Midwest Cogeneration Association) Conference on Energy Policy: The Case for CHP (Combined Heat and Power) in Chicago, IL.
- George Gross gave an invited talk at the Shmuel Oren Symposium at the University of California, Berkeley.

MARCH

- Arijit Banerjee, Philip Krein and Andrew Stillwell attended the IEEE Applied Power Electronics Conference (APEC) and Philip Krein attended committee meetings of the IEEE Power Electronics Society (PELS) in Anaheim, CA.

- Kiruba Haran gave an invited talk at SAE International Aerotech in Charleston, SC.

APRIL

- Kiruba Haran presented an invited seminar at ARPA-E in Washington, DC.

- Arijit Banerjee served as a panelist for the National Science Foundation (NSF) in Washington, DC.

- Philip Krein gave an invited lecture at the opening ceremonies of the Lingang Power Electronics Research Institute in Shanghai, China.

MAY

- Philip Krein attended the IEEE International Electric Machines and Drives Conference (IEMDC) and met with Grainger CEME collaborators in San Diego, CA.

- George Gross directed the 2019 Transmission Business School held in Chicago from May 13 – 17 and participated as a faculty member in this annual training offered to the power industry.

- Subhonmesh Bose and Alejandro Domínguez-García attended the Power Systems Engineering Research Center (PSERC) Industry Advisory Board (IAB) Meeting and Alejandro Domínguez-García attended the Executive Committee Meeting at the University of Wisconsin at Madison, Madison, WI.

- Kiruba Haran presented at the Interagency Advanced Power Group (IAPG) Mechanical Working Group (MWG) meeting at NASA Johnson Space Center in Houston, TX.

- Philip Krein attended the IEEE International Symposium on Power Semiconductor Devices and ICs (ISPSD) in Shanghai, China.

- Arijit Banerjee gave an invited lecture for Scheme for Promotion of Academic and Research Collaboration (SPARC) at IIEST Shibpur, India.

JUNE

- Arijit Banerjee attended the DOE Vehicle Technologies Office (VTO) Annual Merit Review (AMR) in Arlington, VA.

- George Gross visited Universidad Nacional de La Plata and several Argentinian technical societies during a three-week visit as a Fulbright Specialist under the Department of State sponsorship.

- Philip Krein participated at the IEEE History Event: Milestone plaque unveiling of the former General Electric's (GE) site at Advanced Atomization Technologies (AA TECH) in

Clyde, NY.

- Philip Krein attended the IEEE Workshop on Control, Modeling and Simulation in Power Electronics (COMPEL) in Toronto, Ontario, Canada.

- George Gross gave an invited talk at the *Renewable Energy, Storage, Planning and Reliability in Argentina Symposium* in Buenos Aires, Argentina.

JULY

- Arijit Banerjee attended the ARPA-E Energy Innovation Summit (The Summit) in Denver, CO.

- George Gross was a member of the faculty of the University of Salerno Summer School on Smart Grids, held annually in Salerno since 2015.

- Kiruba Haran gave an invited talk at the 2019 Cryogenic Engineering Conference (CEC) and International Cryogenic Materials Conference (ICMC) in Hartford, CT.

AUGUST

- Subhonmesh Bose, George Gross and Kiruba Haran presented at the IEEE PES General Meeting in Atlanta, GA.

- Arijit Banerjee and Kiruba Haran gave invited talks at the ARPA-E Next Generation of Electric Motors for Electric/Hybrid Aviation Workshop in Arlington, VA.

- Subhonmesh Bose gave an invited talk at the Modeling and Optimization: Theory and Applications (MOPTA) Conference at Lehigh University in Bethlehem, PA.

- Philip Krein chaired a panel session and Kiruba Haran presented an invited talk at the AIAA/IEEE Electric Aircraft Technologies Symposium (EATS) Symposium and AIAA Propulsion and Energy Forum in Indianapolis, IN.

SEPTEMBER

- Alejandro Domínguez-García presented an invited talk at the Installation Energy & Water FY20 Solicitation Selection Meeting in Arlington, VA.

- Arijit Banerjee presented an invited talk at the University of Michigan, Ann Arbor, MI.

- Arijit Banerjee presented an invited talk at the Massachusetts Institute of Technology (MIT), Cambridge, MA.

- Arijit Banerjee, Philip Krein and Andrew Stillwell attended the 2019 IEEE Energy Conversion Congress (ECCE) & Exposition in Baltimore, MD.

- Alejandro Domínguez-García gave invited talks at MIT and MIT Lincoln Laboratory in Cambridge and Lexington, MA.

OCTOBER

- Philip Krein attended the US National Academy of Engineering (NAE) Annual Meeting and NAE Section 6 Committee in Washington, DC.

- Arijit Banerjee attended the American Wind Energy Association (AWEA) Offshore WINDPOWER 2019 Conference in Boston, MA and then presented at The New York State Energy Research & Development Authority (NYSERDA) in Albany, NY.

- Alejandro Domínguez-García participated at the Energy Education Council (EEC) Board October Strategic Planning Retreat in Springfield, IL.

NOVEMBER

- Arijit Banerjee and Alejandro Domínguez-García participated at the NSF Workshop on Power Electronics-Enabled Operation of Power Systems in Chicago, IL.

- Alejandro Domínguez-García presented a keynote speech at the Symposium on Machine Learning, Optimization, and Security for Future Energy Delivery Systems at IEEE GlobalSIP'19 in Ottawa, Canada.

- Kiruba Haran attended the RPI (Rensselaer Polytechnic Institute) Electrical Engineering, and Computer, and Systems Engineering (ECSE) Advisory Council Meeting in Troy, NY.

- Arijit Banerjee participated at the 2nd Workshop on Future Trends and Opportunities for Power Electronics in an Electrified Transportation Industry at University of Texas at Dallas, Dallas, TX.

DECEMBER

- Alejandro Domínguez-García, George Gross and Richard Zhang attended the PSERC IAB meeting in Richmond, VA.

- Philip Krein presented an invited lecture at the Huazhong University of Science and Technology in Wuhan, China.

- Richard Zhang participated at Neural Information Processing Systems (NeurIPS) 2019 in Vancouver, Canada.

- Last day of active work for Peter W. Sauer.

During the 2019 calendar year, the power area group hosted the following guest speakers:

- Richard Munson, Author and Director of Midwest Clean Energy for the Environmental Defense Fund, "Tesla: Inventor of the Modern," February.
- Prof. Heath Hofman, University of Michigan, "Simultaneous Identification and Control of Electric Powertrains," March.
- Jay Prigmore II, Ph.D., P.E., Managing Engineer, Exponent, "Recent Failure Investigations in the Power Industry," March.
- Matt Magill, R&D Electronics Engineer, Sandia National Laboratories, September.
- Kathleen Amm, Division Head, Superconducting Magnet Division at Brookhaven National Lab, "Superconducting Magnet Programs: Past, Present and Future," October.
- Dr. Hao Huang, Technology Chief - Electrical Power, GE Aviation, "New Roadmap and Challenges in the New Aviation Era," October.

During the 2019 calendar year, the power faculty and students presented the following seminars to our local audiences:

- Avinash Madavan, “Risk-Sensitive Security-Constrained Economic Dispatch via Critical Region Exploration” and Thanatheepan Balachandran, “Feasibility Study and Optimal Design of A 10MW Air-Core Fully SC Machine for Offshore Wind Turbine.” February.

- Mariola Ndrio, “Coordinated Transaction Scheduling in Multi-ISO Grid Markets with Strategic Players” and Christopher Sain, “An OpenDSS Implementation of a Generic Municipal Microgrid for Co-simulation,” March.

- Phuc Huynh, “Wind Turbine Maximum Power Point Tracking via Integrated Generator-Rectifier System” and Elie Libbos, “Variable Pole Induction Machines for Electric Vehicles,” April.

- Shivang, “Torque-Density Improvement in Brushless Doubly-Fed Reluctance Machines using Additional Stator Winding” and Bonhyun Ku, “A Distributed and Scalable Electromechanical Actuator for Bio-Inspired Robots,” April.

- Adriano Lima Abrantes, “Towards a Meaningful Power System Flexibility Metric” and Yuyao Wang, “Position Estimation of Outer Rotor PMSM Using Linear Hall Effect Sensors and Neural Networks,” April.

- Jonathan Schuh, “Toward Sensor-less Control: Modeling of a Permanent Magnet Magnetic Actuator,” April.

## 6. STUDENT PROJECTS

This section of the report contains information on the graduate students whose major research efforts were supervised by faculty in the Power and Energy Systems Area. While not all of these students received financial aid from the Power Affiliates Program in terms of Research Assistantships, they were all associated with the program through the active involvement of their respective advisors. Those students supported by the Power Affiliates Program received maximum one-half time Research Assistantships for 11 months. The results of each student's work will be made available to all affiliate companies in the form of technical reports. The following students were associated with the Power and Energy Systems Area and their work is described in the following pages:

Agrawal, Shivang (Ph.D.)
Anderson, Aaron (M.S.)
Balachandran, Thanatheepan (Ph.D.)
Barth, Christopher (Ph.D.)
Buason, Paprapee (M.S.)
Chapagain, Prerak (M.S.)
Chattopadhyay, Abhiroop (M.S.)
Cheng, Leslie (M.S.)
Culler, Megan (M.S.)
Das, Dipanjan (Ph.D.)
Dasgupta, Sujay (M.S.)
Feldman, Joshua (M.S.)
Foulkes, Thomas (Ph.D.)
Galtieri, Jason (Ph.D.)
Hoole, Yovahn (M.S.)
Huynh, Phuc (Ph.D.)
Jiang, Wentao (M.S.)
Jin, Qichen (M.S.)
Ku, Bonhyun (M.S.)
Libbos, Elie (M.S.)
Lima Abrantes, Adriano (Ph.D.)
Madavan, Avinash (Ph.D.)
Mamalis, Theodoros (M.S.)
Min, Byung Hoon (M.S.)
Ndrio, Mariola (Ph.D.)
Nigam, Siddhartha (Ph.D.)
Sain, Christopher (M.S.)
Sirimanna, Samith (Ph.D.)
Stillwell, Andrew (Ph.D.)
Wang, Patrick (M.S.)
Wang, Yuyao (M.S.)
Winnicki, Anna (M.S.)
Wu, Michael (M.S.)
Xiao, Jianqiao (M.S.)
Xu, Hanchen (Ph.D.)
Yi, Xuan (Ph.D.)
Yoon, Andy (Ph.D.)
Yu, Yangxue (M.S.)
Zhang, Xiaolong (Ph.D.)
Zholbaryssov, Madi (Ph.D.)
Zhu, Jeffrey (M.S.)

**Shivang Agrawal**

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|---|---|
| B.S.: | May 2016, Indian Institute of Technology (IIT), Kharagpur, India |
| M.S.: | December 2019, University of Illinois Urbana-Champaign |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Doubly-fed Machines, Electric Drives |

**Brushless Doubly-Fed Reluctance Machines for Turboelectric Distributed Propulsion Systems**

Shivang with Advisor Prof. Arijit Banerjee

Supported by NASA and ECE Indirect Cost Recovery

ABSTRACT

Turboelectric propulsion uses no batteries for propulsive energy during any phase of flight (unlike hybrid and all-electric systems) and is considered a critical enabler for low-carbon emissions in the aircraft industry. As batteries with high enough power capacity and the specific power required for commercial aircraft are unlikely to be developed within the next 30 years, turboelectric systems are the only feasible option.

A brushless doubly-fed machine (BDFM) is an attractive option for megawatt-scale turbo-electric propulsion systems due to use of a partially-rated power converter, reduced maintenance, and absence of permanent magnets. However, the BDFM has inherently poor torque density because of machine saturation, even at low current-density. This offsets all the benefits. We have proposed an approach to maximize the torque density by finding appropriate electrical excitations on the two stator windings for a given machine dimension while remaining within flux- and current-density limits. Machine torque capability is enhanced by 75% for an identical machine dimension while simultaneously improving the power factor of the secondary stator, and hence reducing the power converter size. Overall efficiency is also increased with the proposed design.

**Aaron Anderson**

B.S.: May 2017, Purdue University

Status: Working towards M.S. at University of Illinois Urbana-Champaign

Professional Interests: Electric Machines and Drives, Electric Vehicles

## System-Weight Comparison between Motor Topologies for Aircraft Propulsion

Aaron Anderson with Advisor Prof. Kiruba S. Haran

Supported by Grainger CEME

ABSTRACT

An important thrust in current aerospace research is aircraft electrification, including propulsion system electrification. Several system configurations have been explored, including partially distributed, fully distributed, and parallel hybrid propulsion schemes in the NASA N3-X, NASA STARC-ABL, and Rolls-Royce Electrically Variable Engine, respectively. For the electric systems to provide net benefits over traditional aircraft, strict system-specific power, power density, and efficiency requirements must be met. This work takes a rigorous approach in comparing electric machine topologies for electric aircraft propulsors while considering tradeoffs in the power electronic, fault-response equipment, and gearbox components. Permanent magnet synchronous machine, brushless dc machine, switched reluctance machine, and brushless doubly-fed reluctance machine topologies are explored. Models are developed employing analytical sizing equations calibrated using advanced machines found in the literature and industry trends. Continuation of this work will include modeling each machine in a finite element analysis tool to determine design validity and obtain more accurate efficiencies and weights, and more detailed power electronic models, while carefully considering the impact of system efficiency on thermal management systems, additional energy storage, and airframe size.

**Thanatheepan Balachandran**

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| B.S.: | University of Peradeniya, Sri Lanka. |
| M.S.: | Wichita State University, Wichita, KS |
| Status: | Working towards Ph.D. at University of Illinois at Urbana Champaign |
| Professional Interests: | Superconducting Machines, Renewable energy, Electric aviation |


## Feasibility Study on Superconducting Motor Topologies for Hydrogen Powered All Electric Commercial Aircraft

Thanatheepan Balachandran with Advisor Prof. Kiruba S. Haran

Supported by NASA and CHEETA

ABSTRACT

The Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA) is a NASA-funded project that aims to design an ultra-efficient (99%) electrical system with the high specific power (>25 kW/kg) required for commercial electric aircraft. The system uses liquid hydrogen both as the energy source for the fuel cells and as the cryogen for the electrical system. This eliminates additional cryogenic system weight and opens up the propulsion system design space to consider various motor topologies which leverage superconducting (SC) technologies. Furthermore, operating the electrical system under the cryogenic system also enables various advantages, such as low resistivity of "conventional" conductors like copper or aluminum. This project considers a 40 MW regional airplane for six hours of operation and analyzes the feasibility of three motor topologies for its electric propulsion: (1) fully superconducting machine with active shield and iron shield configuration, (2) partially superconducting machine with active shield and iron shield configuration, and (3) permanent magnet machine with SC armature coils and cryocooled conventional conductors. Pros and cons of each topology at the required power level are analyzed, and the optimal motor topology for implementing commercial electric aircraft is identified. Efficiency and specific power are used as the metrics to compare the motor topologies. To obtain a fair comparison, each motor is optimized to maximize its efficiency and specific power.

**Christopher Barth**

B.S.: December 2012, University of Illinois Urbana-Champaign

M.S.: December 2014, University of Illinois Urbana-Champaign

Ph.D.: December 2019, University of Illinois Urbana-Champaign

## Design of High-Density Inverters for Photovoltaic and Motor Drive Applications

Christopher Barth with Adviser Prof. Robert Pilawa-Podgurski

Supported by Grainger CEME

### Abstract

Traditionally, inverters have employed a minimal number of active switching components and used large passive inductors to filter two- or three-level voltages into sinusoidal currents. This results in a relatively simple system with acceptable performance characteristics. Newer inverter designs are seeking to minimize system volume and weight while maintaining or improving efficiency and performance. Because capacitor energy density has been shown to be around two orders of magnitude higher than that of inductors, one method of increasing power density is through using more capacitors as filtering components rather than inductors in inverter designs. Inverters, such as modular multilevel and flying capacitor, use a higher number of active switches and require advanced control strategies. Research is being done in the control of many parallel sub-inverters in order to develop increased reliability. These inverters can be coordinated to partially meet system requirements, even during a failure event of a few of the submodules.

**Paprapee Buason**

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| B.S.: | May 2016, University of Illinois Urbana-Champaign |
| M.S.: | May 2019, at University of Illinois Urbana-Champaign |
| Professional Interests: | Dynamic and Stability of Power Systems, Microgrid Modeling and Simulation, Real-time Simulation, Cyber Security of Microgrids |


## Dynamics and Stability of Microgrids

Paprapee Buason with Advisor Prof. Emeritus Peter Sauer

Supported by Information Trust Institute (ITI) and ABB Inc.

ABSTRACT

Microgrids are being adopted in distribution systems to increase resiliency in power systems. Modern microgrids rely on sophisticated communication and controls, which lead them to require interaction with cyber-physical systems. In this research, I present control strategies and approaches for resiliency to attacks against measurements, while increasing system stability and secure communications within microgrids, when microgrids are in islanded mode. The sequence of operations to continuously serve specific critical loads is discussed. Finally, a use case that unifies all concepts is included. This case serves to mitigate effects of an attack against measurements on a critical load bus. Firstly, the attack is detected by the mean of the detection algorithm. Then, the suspicious distributed energy resource is tripped off due to the command from COM600, which calculates the preventive algorithm called *Reachability Analysis*. The appropriate tie line between two microgrids is closed to continuously supply power to the critical load when consensus is reached. Control strategies and communication take action to ensure stability of the new system. Results from real-time simulation are provided to validate the effectiveness of this approach.

**Prerak Chapagain**

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| B.S.: | University of New Orleans |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Optimization, Smart Grid, Renewables |


## Security Enhancements in IEEE-1547 Environments Integrating DER and Area Power Systems

Prerak Chapagain with Advisor Emeritus Prof. Emeritus Peter Sauer

Supported by ITI and ABB Inc.

ABSTRACT

It is evident that the rise of renewables has increased the number of distributed energy resources (DERs). The grid is thus expected to experience a high penetration of DERs. Thus, the IEEE 1547 standard from 2003 needed a major revision. The new IEEE standard recently revised in 2018 makes sure the integration of DERs is smooth and convenient. The new grid standard is subjected to voltage regulation, response to unintentional islanding, control during intentional islanding, component ride-through in the event of tolerable system anomalies, and electrical and communication interfaces between DER or aggregated DER facilities with an area electric power system. Since shutting down large numbers of DERs impacts the grid in multiple ways, new DERs are supposed to be more robust in terms of handling voltage and frequency fluctuations and have ride-through capabilities. This coupling of DERs with the grid raises numerous cybersecurity threats. Thus, with the help of sponsors like ABB and Duke Energy, we seek to identify different possible threats, simulate a sample circuit using real-time software such as OPAL-RT, and understand potential attack vectors.

**Abhiroop Chattopadhyay**

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| B.S.: | December 2014, Illinois Institute of Technology, Chicago, IL |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Cybersecurity in Power Systems, Flexible AC Transmission Systems |

**Cybersecurity Vulnerabilities of Wide-Area Controlled FACTS Devices in Power Systems**

Abhiroop Chattopadhyay with Advisor Prof. George Gross

Supported by ITI

ABSTRACT

Flexible ac transmission system (FACTS) devices in power systems are increasingly deployed to enhance resiliency and operational robustness. Present FACTS devices have limited configurability and interoperability features, often requiring on-site presence for reconfiguration. We may envision future FACTS with the ability to support communication (measurement and control commands) as well as collaborative operation in support of use cases such as distributed operation for oscillation damping. This evolution potentially exposes a cyberattack surface. Our purpose is to understand cyberattack pathways into future FACTS deployments, and their interface to wide-area measurement, protection, and control, in order to develop mitigation strategies. In this way, we seek to remove barriers to realizing the benefits of modern FACTS ecosystems enabled by a secure cyber layer for measurement and control. We also seek to develop potential metrics of the criticality of threats to understand the impacts on a power system due to the alteration or loss of information from the system.

**Leslie Cheng**

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| B.S.: | May 2017, University of Illinois at Urbana-Champaign |
| M.S.: | May 2019, University of Illinois at Urbana-Champaign |
| Professional Interests: | Electric Machinery, Power Electronics, and Electric Vehicles |


**Ring-Motor Front Wheel for Electric Motorcycle Applications**

Leslie Cheng with Advisor Prof. Kiruba S. Haran

Supported by the NASA

ABSTRACT

Electric vehicles have gained popularity and become prominent in recent years. Small companies, such as Zero Motorcycles, address a niche by producing electric motorcycles. Many electric vehicle designs allow for unconventional choices not possible in gas vehicles, such as Tesla vehicles where the typical engine compartment area is now storage space. However, modern electric motorcycles have a nearly identical layout to gas motorcycles where an electric machine replaces the engine to drive the rear wheel. The addition of a powered front wheel is often omitted due to mechanical complexity for gas motorcycles, but electric motorcycles are not subject to this because a motor could be integrated within the wheel. This work examines and explores the performance of such a machine. Increased acceleration and traction are expected due to an additional source of movement. However, it lacks the gear reductions of the conventional layout. Cooling is also a challenge due to exposure to dirt and debris.

**Megan Culler**

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| B.S.: | May 2019, Texas A&M University |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Cybersecurity for Power Systems and Industrial Control Systems, Secure Power Distribution |


## Cybersecurity Evaluation of Updated IEEE 1547 for DER Interconnection and Interoperability

Megan Culler with Advisor Prof. Emeritus Peter Sauer

Supported by ITI and ABB Inc.

ABSTRACT

The 2018 revision of the IEEE 1547 standard was written to account for the growing penetration of renewables and other distributed energy resources (DER) into the generation profile. The original standard from 2003 states that DER should disconnect when grid disturbances occur. However, with the higher penetration of DER, tripping off could exacerbate a grid disturbance, so the updated standard calls for increased ride-through tolerance from DER and grid support services. While the development of this standard is necessary for grid stability with high DER penetration, it does not adequately address cybersecurity issues. This project considers the cybersecurity implications of the updated standard. We first consider the feasible range of cybersecurity threats that are new and unique to the updated standard and explore the requirements for a successful attack path. We evaluate the system constraints for a successful attack, as well as the skills needed for an adversary to achieve a goal of destabilization. Then we simulate the impact of an attack performed by creating a malicious but syntactically correct message that causes a destabilizing action to occur under certain conditions. We will record normal, abnormal, and malicious patterns of communications to provide a feasible defense strategy to remote cyber-physical attacks on the points of interconnection for the distributed energy resources. The goal of the defense research is to help establish a root of trust between the utility and the third party DER operator. The results will show that there are new cyberattack surfaces threatening the stability of grids with the implementation of the updated IEEE 1547 standard. Further research is required to determine methods to mitigate the vulnerabilities introduced.

**Dipanjan Das**

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| B.S.: | July 2013, Indian Institute of Technology, Kharagpur |
| M.S.: | May 2016, University of Illinois Urbana-Champaign |
| Ph.D.: | May 2020, University of Illinois Urbana-Champaign |
| Professional Interests: | Power Electronics, Control of Power Electronics, DC-DC Converters |


## Differential Power Processing for Voltage Regulation of Low Voltage Loads

Dipanjan Das with Advisor Prof. Emeritus Philip T. Krein

Supported by Grainger CEME

ABSTRACT

Power delivery to multi-core processors is becoming increasingly challenging with decreasing transistor sizes and, thereby, their operating voltages. With the expansion in number in each processor, the power requirements tend to remain the same with each new generation of microprocessors, and handling transient performance requirements along with efficiency has become much more difficult at lower voltages. Significant improvement in energy efficiency can be achieved by stacking the processor cores in series and regulating the core voltages by differential power processing (DPP).

However, for practically achieving higher efficiency than the conventional parallel-connected processor core architecture over a wide load range, special importance must be given to light-load power management of bidirectional DPP converters in such a series-stacked system. Topological and control strategies (bidirectional light-load control, multiphase converters with asymmetric load sharing, phase shedding) for faster transient response as well as converter efficiency improvement over a wide bidirectional power range for DPP converters is being investigated.

**Sujay Dasgupta**

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| B.S.: | May 2017, Nirma University, Ahmedabad, India |
| MEng: | December 2018, University of Illinois at Urbana Champaign |
| Status: | Working towards M.S at University of Illinois Urbana-Champaign |
| Professional Interests: | HVDC & Microgrid Modeling, Real-time Simulation, Power System Dynamics and Stability, State Estimation, Cybersecurity of Power System |

**Improving Grid Resiliency using FACTS and HVDC**

Sujay Dasgupta with Advisor Prof. Emeritus Peter Sauer

Supported by ITI and ABB Inc.

ABSTRACT

The project scopes are identifying and securing cyber-attack surfaces for coordinated FACTS and control schemes using communication layers such as wide-area monitoring, protection, and control to better understand transient stability limits, power system oscillation limits. Also, securing high voltage direct current (HVDC) systems as these interfaces to transmission systems. This is based on real-time state estimation of the entire system. As HVDC power injections change, we continuously evaluate the consistency of an HVDC power request, while simultaneously monitoring system stability and the consistency of measurements as a power injection ramps. Comparison of measurements with the estimated state helps us assess whether a valid power order was correctly carried out. We are looking into protocols such as DNP3 for the power order, and modeling systems such as PowerWorld, MATPOWER, and RTDS for the modeling.

**Joshua Feldman**

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| B.S.: | May 2019, Mechanical Engineering |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Electric Machines, Cryogenics, Thermal Management |


## Design and Test of a Cryogenic Cooling System for a Fully Superconducting Machine

Joshua Feldman and Advisor Prof. Kiruba S. Haran

Supported by NASA

ABSTRACT

A cryogenic cooling system is needed to maintain a proposed fully superconducting motor at temperatures near 20 K. The motor is proposed as part of the Center for High-Efficiency Electric Technologies for Aircraft, which aims to research and develop technologies needed for fully electric commercial aircraft. The cooling system will use liquid hydrogen at 20 K to remove losses from the motor, which are dominated by ac losses associated with high-frequency machines. Motor temperature, temperature uniformity, cooling system weight, and size are all primary considerations in the design process. Hardware tests will be performed to explore the viability of the proposed design.

**Thomas Foulkes**

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| B.S.: | May 2015, Rose-Hulman Institute of Technology |
| M.S.: | May 2017, University of Illinois at Urbana-Champaign |
| Ph.D.: | December 2019, University of Illinois Urbana-Champaign |
| Professional Interests: | High Power Density Converter Design, Magnetic and Dielectric Material Analysis, Thermal and EMI Mitigation |


## Liquid-Bridge Confined Boiling for Thermal Management of High-Power Density Electronics

Thomas Foulkes with Advisors Prof. Nenad Miljkovic and Prof. Robert Pilawa-Podgurski

Supported by NSF Graduate Research Fellowship, NASA and POETS

ABSTRACT

Increasing electrification of mechanically controlled or driven systems has created a demand for the development of compact, lightweight electronics. Removing waste heat from these high volumetric and gravimetric power-dense assemblies, especially in mobile applications, requires non-traditional thermal management strategies with high heat-flux potential and low integration penalty. To overcome this obstacle, a thermal management technique involving confined, sub-cooled pool boiling on nanoengineered surfaces was created. This enables self-assembly of liquid bridges capable of high heat-flux dissipation without external pumping. Using high-speed optical imaging coupled with high-fidelity heat-transfer experiments in pure vapor environments, we study the physics of liquid bridge formation, bridge lifetime, and heat transfer. Heat flux dissipations greater than 100 W/cm$^2$ were demonstrated from a gallium nitride power transistor residing above a horizontally parallel, super-hydrophobic, nanostructured aluminum cold plate. To understand the confined-bridge dynamics, a hydrodynamic droplet-bridging model and design rules were developed capable of predicting the effects of gravity, intrinsic contact angle, contact angle hysteresis, and device heat flux. This work not only demonstrates an ultra-efficient mechanism of heat dissipation and spreading using nanoengineered surfaces coupled to fluid confinement, it also enables the development of three-dimensional integrated electronics.

**Jason Galtieri**

B.S.: May 2013, University of Connecticut

M.S.: May 2015, University of Illinois Urbana-Champaign

Ph.D.: August 2019, University of Illinois Urbana-Champaign

Professional Interests: Power Electronics and Renewable Energy

**Solar Variability Reduction in Solar Arrays Using Off-MPP Tracking and Energy Storage Systems**

Jason Galtieri with Advisor Prof. Emeritus Philip T. Krein

Supported by Grainger CEME

ABSTRACT

Maximum power point (MPP) tracking is the standard control scheme for photovoltaic (PV) arrays of all sizes. Inverter tracking algorithms work on second to sub-second time scales and can track most naturally occurring irradiance changes, such as moving cloud coverage. Fast-response tracking imposes large power swings on the grid, which must be absorbed in spinning reverses. As PV penetration increases and replaces traditional spinning generation, there is concern the grid's voltage and frequency stability could be compromised.

The ability to operate PV panels predictably at set points away from their MPP opens a wide range of possibilities for PV array control and support. However, off-MPP set points lose many of the constraints traditional maximum power trackers require to correctly function. This work proposes an off-MPP set-point strategy that uses ripple correlation control (RCC) to quickly find the MPP current and voltage. The MPP data is then fed into a set-point controller, to operate at a reduced set point. RCC algorithms converge in millisecond timeframes, so the MPP data can be updated several times a second to maintain accuracy. Likewise, the off-MPP converters converge on similar time scales, so the converters spend most of their time at the reduced set point.

**Yovahn Hoole**

B.S.: 2018, Rice University

Status: Working towards M.S. at University of Illinois Urbana-Champaign

Professional Interests: Electric Machines and Drives, Electric Transportation

## Hall-Effect Sensor Based Rotor-Position Transducer

Yovahn Hoole with Advisor Prof. Kiruba S. Haran

Supported by ECE Indirect Cost Recovery (ICR)

ABSTRACT

To extract peak performance from permanent magnet synchronous machines, the drive system requires accurate position feedback of the rotor angle to align the current vector and achieve maximum torque output. Traditionally, this was fulfilled by the integration of a position transducer with the motor shaft, such as an encoder or resolver. That increases system cost and mechanical complexity. An alternative to the transducers is back-emf or high-frequency signal-injection based sensorless methods. However, back-emf based methods are unable to estimate rotor position accurately at low speeds due to reduced signal amplitudes, and while signal-injection based methods will work well at low and zero speeds, these rely on either inherent saliency in the machine, or anisotropy due to saturation effects in non-salient machines. The use of linear Hall-effect sensors to measure the external leakage magnetic flux of the rotor provides an alternative that is easier to implement than sensorless methods. These sensors are able to operate at low and zero speeds and are cheaper than including a position transducer. This work proposes a neural-network algorithm to interpret the signals, obtained from linear Hall-effect sensors located in the rotor fringe field, to replace traditional resolvers. The main objective is to design a cost-effective position-estimation system comparable to encoders and resolvers in functionality and performance, without the limitations of sensorless position-estimation methods.

**Phuc Huynh**

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| B.S.: | December 2013, University of Minnesota |
| M.S.: | December 2016, University of Illinois Urbana-Champaign |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Electric Machine and Power Electronics Integration, Power System Dynamics and Control |


**An Integrated Generator-Rectifier System for Limited-Speed-Range Applications**

Phuc Huynh with Advisor Prof. Arijit Banerjee

Supported by ARPA-E

ABSTRACT

Ac-to-dc power conversion is essential in many emerging applications, including wind-power generation and electrified transportation. For example, an intermediate dc bus is often necessary to connect a variable-speed wind-powered generator to the fixed-frequency ac grid. Similarly, future electric ships are envisioned to have a medium-voltage dc grid created from a gas-turbine driven ac generator. The electrical output of these megawatt-scale mechanical-to electrical energy conversion systems is a regulated dc bus while the prime movers operate over a limited speed range. The speed range is driven by an improved energy-captured-to-cost ratio, as in a wind turbine, or by an increased fuel efficiency, as in a gas-turbine driven generator.

Conventionally, ac-to-dc power requires all power to be processed on active rectifiers, leading to high investment cost, high loss, and reduced reliability. This project develops an ac-to-dc power conversion architecture that integrates power electronics with a multi-port permanent magnet synchronous generator. The architecture relies on series-stacking one active with multiple passive rectifiers. This system achieves high conversion efficiency by processing most of the power on the passive rectifiers. In addition, overall system reliability could potentially increase at a reduced investment cost.

The project has been funded starting June 2019 by the Advanced Project Research Agency – Energy (ARPA-E) through the prestigious ARPA-E Open competition in 2018.

**Wentao Jiang**

B.S.: University of Illinois at Urbana-Champaign

Status: Working towards M.S. at University of Illinois Urbana-Champaign

Professional Interests: Power Electronics

## Four-Level Flying Capacitor Multi-Level Dual Active Bridge Converter

Wentao Jiang with Advisor Prof. Andrew R Stillwell

Supported by ECE Indirect Cost Recovery (ICR)

ABSTRACT

A conventional dual active bridge converter has single-level H bridges on the input and output side. The voltage stress of the switches increases with the input and output voltage. To reduce the voltage stress of the switches, two flying capacitor multi-level (FCML) structures can be used to replace the H bridge on the input side. Faster, commercially available power switches such as GaN can then be used with the lowered voltage stress. The voltage stress of the auxiliary inductor can also be decreased, which increases the power density as the volume of the inductor is reduced. FCML also offers flexibility in the converter design. Modifying the number of stages in one of the FCML structures by simply shorting nodes in the circuit allows switching between full-bridge and half-bridge operation modes. The combination of these two popular topologies also adds isolation to the FCML structure, a common requirement for many applications.

**Qichen Jin**

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| B.S.: | May 2019, University of Illinois at Urbana Champaign |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Power Electronics, Electrical Machines |

**Health Monitoring of IGBTs for High-Speed Trains**

Qichen Jin with Advisor Prof. Arijit Banerjee

Supported by CRRC China

ABSTRACT

Power converters have become indispensable to our modern day electronics devices/electric systems. The study of power-converter reliability is crucial for electrical transportation, including electric vehicles and electric trains. Malfunction of active switches is a major cause of failure in power converters. Currently I am helping Michael Wu in developing a health-monitoring system for IGBTs. It is implemented by adding measuring circuity to predict the remaining life of IGBTs in real time. If one IGBT is predicted to fail or has reached its lifetime, it can be replaced before the IGBTs fail to operate.

**Bonhyun Ku**

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| B.S.: | December 2016, University of Texas at Dallas |
| M.S.: | December 2019, University of Illinois at Urbana-Champaign |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Robotic Actuators, Power Electronics and Control |


## A Distributed Electromechanical Spine for Bio-Inspired Robots

Bonhyun Ku with Advisor Prof. Arijit Banerjee

Supported by NSF and Kwanjeong Educational Foundation

ABSTRACT

Biological mechanisms are embraced in mobile robots to interact with their surroundings. Although current bio-inspired robots perform well, their performance is limited due to the lack of a flexible spine. A spine provides an animal's agility, a wide range of motion, balance, and efficiency. It can be created with motors, which have been widely used for robotic joints. However, this introduces design complexity, low actuation speed, poor back drivability, and backlash issues. This project develops a distributed and scalable two-dimensional electromechanical spine for bio-inspired robots. It provides an approach that mimics an actual animal spinal structure and muscles by combining a magnetic core and two coils in a module. Six modules are connected in series to form a spine. A single module and the entire system represent a vertebra and vertebrae, respectively. The proposed actuator utilizes electromagnetic force induced by coil currents to control torque at each module. This actuator has several benefits, including modularity, scalability, distributed actuation, simple structure, and gearless design, as well as a better cooling mechanism. A distributed air-gap model is proposed to improve force estimation by taking non-uniform air gaps and core saturation into consideration. A torsion spring mechanism is applied to each module to improve torque capability.

**Elie Libbos**

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|---|---|
| B.S.: | American University of Beirut |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Electric Machines and Drives, Power Electronics, Control |


**Variable-pole Induction Machine Drive for Electric Vehicles**

Elie Libbos with Advisor Prof. Arijit Banerjee

Supported by ECE Indirect Cost Recovery (ICR) and the Navy

ABSTRACT

High power density, high efficiency, inexpensive drivetrains operating over a wide torque/speed range are critical for traction applications. An induction machine (IM) offers a cost-effective, rugged and reliable alternative to permanent magnet solutions. Varying the IM's pole count on-the-fly extends the machine's operating regime over a wide speed range. Because traction drivetrains rarely operate at rated conditions, the pole count is judiciously selected to minimize drivetrain losses and stator current over all loading conditions. We investigate the co-design and control of a variable-pole IM and its modular multiphase drive for electric vehicles. An experimental setup consisting of an 18-phase GaN-based drive and a 36-slot toroidally wound IM is used to validate the theory.

**Adriano Lima Abrantes**

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| B.S.: | December 2013, University of São Paulo, Brazil |
| M.S.: | August 2016, University of São Paulo, Brazil |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Power System Flexibility, Renewable Integration, Electricity Markets |


**A Stochastic Simulation Framework for Grid Operational Flexibility Assessment**

Adriano Lima Abrantes with Advisor Prof. George Gross

Supported by Power Systems Engineering Research Center (PSERC) and Grainger Foundation

ABSTRACT

Deeper penetration of integrated variable-energy resources in electric power systems increases the uncertainty and variability in the net load – the demand that must be met by controllable generation resources – and thus requires clear understanding and a quantified assessment of grid operational flexibility and its associated impacts. The lack of a widely accepted methodology to assess grid operational flexibility and the absence of metrics for its measure pose major challenges to power systems operators and planners. The quantification of grid operational flexibility (GOF) is challenging due to its multifaceted nature, as it is connected to multiple timescales, time horizons, operational limitations of generating units, networks constraints, uncertain renewable power production and grid operational paradigms. Furthermore, the economic aspects of GOF procurement must not be disregarded. In this project, we propose a stochastic simulation framework for power-system flexibility assessment to allow for quantification of economic impacts of grid actions to accommodate effects of net-load variability and uncertainty, including those associated with energy storage and demand-response resources. Our goal is to construct a practical scheme to evaluate various economic-impact based GOF metrics with the time-varying and uncertain behavior of renewable power production and demands. Their corresponding forecasts in day-ahead and real-time operations are explicitly represented.

**Avinash N. Madavan**

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| B.S.: | May 2016, University of California at San Diego |
| M.S.: | December 2018, University of Illinois Urbana-Champaign |
| Status: | Working towards Ph.D. at University of Illinois at Urbana-Champaign |
| Professional Interests: | Risk-sensitive Convex Optimization |


## Risk-Sensitive Energy Procurement under Uncertain Wind

Avinash N. Madavan with Advisor Prof. Subhonmesh Bose

Supported by the International Institute for Carbon-Neutral Energy Research (I2CNER)
and Power Systems Engineering Research Center (PSERC)

ABSTRACT

System operators (SOs) routinely solve economic dispatch problems ahead of real time to make dispatch decisions. Increasing renewable penetration and widespread adoption of distributed energy resources has resulted in greater uncertainty in these forward-energy procurement problems. As forecasts deviate more significantly from real-time operation, SOs must both be able to model this uncertainty and take it under consideration when solving forward-energy procurement problems. However, they must be able to do so in a way that captures their tolerance towards high cost and constraint violation. We propose the use of conditional value-at-risk (CVaR), a risk measure that has found widespread appeal in financial literature. The CVaR risk measure provides a parameter through which one can express risk aversion. We propose a CVaR-penalized, CVaR-constrained risk-sensitive forward-energy procurement problem. We further propose a primal-dual stochastic sub-gradient algorithm, where dispatch decisions are updated at each iteration, to solve this problem. We are able to provide finite-time convergence guarantees for this algorithm, ensuring convergence to the solution of the risk-sensitive energy procurement problem.

**Theodoros Mamalis**

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| B.S.: | December 2016, University of Patras |
| Status: | Working towards M.S. at University of Illinois at Urbana-Champaign |
| Professional Interests: | Vehicle-to-Grid Services, Transportation Networks, Incentive Modeling, Optimization |


## Electric Vehicles for Grid Services

Theodoros Mamalis with Advisor Prof. Subhonmesh Bose

Supported by ECE Indirect Cost Recovery

ABSTRACT

Electrification of urban transportation is on the rise. In April 2016, Téo Taxi launched a plug-in electric vehicle (PEV) fleet in Montreal, followed four months later by Uber in London. PEV enables transportation but adds to the road traffic. When parked, it can act as a controllable storage device either to consume surplus or inject energy to the grid. Hence, managed PEV fleets provide unique opportunities for electric grid support and traffic management. Further, managed PEV fleets include two types. One comprises ridesharing companies with transactional control over vehicles, wherein private drivers respond to monetary incentives. The other comprises car-sharing companies, which directly control their fleet. In this project, we will characterize viable control strategies for the managers to co-optimize their revenues from both transportation services and their grid activities. We will develop profit maximization algorithms of the PEV fleet managers providing such services.

**Byung Hoon Min**

B.S.: May 2017, University of Illinois, Urbana-Champaign

M.S.: May 2019, University of Illinois Urbana-Champaign

Professional Interests: Electric Machines and Drives, Electric Vehicles, Optimization

**PM-Assisted Synchronous Reluctance Motor as a Compressor Application**

Byung Hoon Min with Advisor Prof. Kiruba S. Haran

Supported by NASA and JCI

ABSTRACT

HVAC systems consume a major portion of energy in both industrial and domestic buildings. Thus, compressor motor efficiency has a huge impact on overall compressor motor efficiency. Currently, the industry relies heavily on an induction motor that is cost-effective compared to regular permanent magnet synchronous machines but lower in efficiency. From initial trade-study research, the PM-assisted synchronous reluctance motor (PM assisted SynRM) with a ferrite magnet seemed to be a viable option for compressor usage. It can be a substitute for an induction motor giving higher efficiency while maintaining lower cost. The PM-assisted SynRM employs reluctance torque in addition to regular magnetic torque, allowing usage of low-cost ferrite magnets instead of permanent magnets. However, mechanical stability is affected due to these magnetic barriers. Current research seeks to optimize rotor design for both higher efficiency and mechanical stability in compressor applications.

**Mariola Ndrio**


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| B.S.: | February 2014, National Technical University of Athens, Greece |
| M.S.: | May 2016, University of Illinois Urbana-Champaign |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Electricity Markets, Game Theory |


## Analysis and Design of Competitive Electricity Markets

Mariola Ndrio with Advisors Prof. Emeritus Peter Sauer and Prof. Subhonmesh Bose

Supported by the Grainger Foundation and PSERC

ABSTRACT

We address several emerging challenges in electricity markets. In the wholesale sector, we analyze existing market-based mechanisms for scheduling power interchanges across interconnected grids that are operated by different entities. Our interests lie in understanding the impacts of strategic market actors in the efficiency of inter-area power schedules. We utilize tools from optimization, economics and game theory to characterize the market outcome and quantify the efficiency loss at the Nash equilibrium. Our analysis indicates that market performance is driven by total liquidity, players' conjectured prices and their possible interactions with other electricity markets. When the market is sufficiently liquid, the worst-case efficiency loss of inter-area markets is 25%. In the retail electricity sector, the increased consumer participation—either as generation suppliers or price-responsive demanders—is driving the emergence of a digital platform marketplace where end-use customers can engage in transactions coordinated via a central entity or market manager. These transformations pose new challenges as to which mechanisms must be in place to incentivize low-voltage resources to offer their services to the grid and appropriately compensate them for those services. To this end, we explore scalar-parameterized supply offers and demand bids for two-sided markets with a centralized clearing mechanism. Moreover, we analyze and propose a set of market prices that retain a number of desired properties and make it a suitable compensation scheme for resources at the distribution network.

**Siddhartha Nigam**

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| B.S.: | May 2014, Vellore Institute Technology, Tamil Nadu, India |
| M.S.: | May 2017, University of Illinois Urbana-Champaign |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Microgrid Modeling, Operations, and Control |


## Controller Hardware in the Loop Testing of Microgrid Secondary Frequency Control Schemes

Siddhartha Nigam with Advisors Prof. Emeritus Peter Sauer and Prof. Alejandro Domínguez-García

Supported by the Grainger Foundation

ABSTRACT

The past decade has seen a sharp rise in the deployment of distributed energy resources (DERs) in electric power grids across the globe. Along with this continuing trend came the microgrid concept, which has been shown to be a promising approach for efficient integration and management of DERs. A microgrid can operate in both grid-connected and islanded modes. In islanded mode, frequency control is a major problem; this is due to the intermittent nature of renewable-based DERs, e.g., photo voltaic installations, and the utilization of power electronic inverters to interface DERs to the microgrid, which leads to low or no rotating inertia. Among the various frequency-control objectives, a key one is secondary frequency control, which entails ensuring that, following a change in operating point of the microgrid, the system-wide frequency returns to its nominal value. This work describes a controller hardware-in-the loop (C-HIL) approach for testing centralized and distributed secondary frequency control schemes of ac microgrids operating in islanded mode. We formulate the secondary frequency-control problem and the theory behind the centralized and distributed implementations of the control schemes. Then, we describe the testbed utilized for C-HIL testing activities. Finally, we provide testing results that compare the performance (in terms of the system response time), and resilience (in terms of withstanding the failure of a control device), of both schemes.

**Christopher Sain**

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| B.S.: | 2017, New Mexico Institute of Mining & Technology |
| M.S.: | May 2019, University of Illinois Urbana-Champaign |
| Professional Interests: | Reliability and Planning in Infrastructure |


## An OpenDSS Implementation of a Generic Municipal Microgrid for Co-Simulation

Christopher Sain with Advisor Prof. Emeritus Peter Sauer

Supported by the Grainger Foundation

ABSTRACT

Many power system research problems may be solved via deployment simulations. However, for real-world problems, the computational efforts for detailed dynamic modeling may be impractical or excessive. OpenDSS provides a framework within which a model of a small- or large-scale system may be implemented, without the representation dynamics, with extensive co-simulation capabilities. We model a generic 8-bus microgrid that consists of 200 residential loads plus an additional load for the local control building, three-generation resources – solar, wind, and gas – and a battery-storage resource. We use actual environmental data from Decatur, IL together with realistic consumer load shapes to analyze the simulation studies of various unbalanced and quasi-balanced situations. In addition, we apply the model in co-simulation studies with hardware-in-the-loop to evaluate various potential scenarios.

**Samith Sirimanna**

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| B.S.: | April 2016, University of Moratuwa, Sri Lanka |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Electric Machine Design, Rotor-dynamics, Machine Drives |


## 10 MW Direct Drive Wind Generator with Low Reactance

Samith Sirimanna with Advisor Prof. Kiruba S. Haran

Supported by ARPA-E

ABSTRACT

Generators used in wind turbine applications include a variety of topologies depending on the power level and the operating speed. Some of the large-scale wind turbine manufacturers show an increasing interest in direct-drive generators, which improve reliability by eliminating the gearbox. Among other candidates, permanent magnet (PM) generators show an advantage in terms of torque density and efficiency.

Recent research by the power and energy group in Illinois has shown that the power electronics cost of a generator can be significantly reduced by introducing multi-port architecture to the generator and by controlling only one port using active switches. However, implementation of this technology requires the per-unit synchronous reactance of the generator to be much smaller than conventional wind generators.

The Illinois power and research group has previously demonstrated the design of a low-inductance, slotless PM synchronous machine for aerospace applications. The same concept of slotless machines is adopted here to enable the low-inductance requirement. In modelling the wind generator with low reactance, a number of parameters are considered, such as the pole count, and geometric variables to optimize the generator topologies for high efficiency and low weight.

**Andrew Stillwell**

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| B.S.: | 2005, University of Missouri |
| M.S.: | August 2015, University of Illinois Urbana-Champaign |
| Ph.D.: | 2019, University of Illinois Urbana-Champaign |
| Professional Interests: | High Power Density Power Converters, Renewable Energy |

**Design Optimization of a 1500 V GaN-Based Solar Inverter Using Flying Capacitor Multi-Level Converter Stages**

Andrew Stillwell with Advisor Prof. Robert Pilawa-Podgurski

Supported by DOE Sunshot Project and Grainger CEME

ABSTRACT

Utility-scale solar installations are adopting 1500 V solar inverters with reduced cabling and installation costs. Flying capacitor multi-level (FCML) inverters with 650 V transistors offer unique system benefits, leading to lower volume and weight while improving system efficiency. In this work, we develop the design optimization of FCML inverters for 1500 V with considerations of different switches, number of levels, switching frequency and passive components. The optimization informed the design of a 5-level FCML with 650~V GaN switches which was demonstrated successfully in hardware.

**Patrick Wang**

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| B.S.: | University of Illinois at Urbana-Champaign |
| Status: | Working towards M.S. at University of Illinois at Urbana-Champaign |
| Professional Interests: | Circuit Design, Power Electronics, Product/Application Engineering |


**Condition Monitoring of Sic MOSFETs Utilizing Gate-Leakage Current**

Patrick Wang with Advisor Prof. Arijit Banerjee

Supported by the US Navy & USNA

ABSTRACT

This research focuses on health monitoring of silicon carbide (SiC) devices. Gate-leakage current is expected in aged SiC MOSFETs, and obtaining a reliable measurement of the gate leakage current can achieve condition monitoring and perhaps even prognostic health monitoring. Due to the transient gate current during switching, measuring the leakage current is challenging. The proposed method attempts to measure the total gate charge over a period of time instead of directly sampling the current at high frequency. This in-situ method allows health monitoring during real-time operation, and the implementation cost is expected to be low. Finally, the circuit will be tested on an LLC resonant converter at 1 kV dc-link voltage and high current to prove its feasibility.

**Yuyao Wang**

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| B.S.: | 2017, National University of Singapore |
| M.S.: | May 2019, University of Illinois Urbana-Champaign |
| Professional Interests: | Electric Machines and Drives, Electric Transportation |


## Position Estimation of Outer Rotor PMSM using Hall Effect Sensors and Neural Networks

Yuyao Wang with Advisor Prof. Kiruba S. Haran

Supported by NASA and Grainger CEME

ABSTRACT

Driving and controlling a permanent magnet synchronous machine requires precise knowledge of the angular position of the rotor, such that the voltages and currents can be applied with the right phase difference to extract maximum torque and efficiency out of the machine. Conventional sensored methods required attachment of a position transducer onto the rotor, increasing cost and complexity. Whereas sensorless methods relied on either injecting a high-frequency signal, or measuring the back-emf from the rotor, and do not perform well at low speeds. An alternative is to use an array of simple hall effect sensors, positioned to measure the leakage magnetic field from the rotor. These measurements are used to train a neural network to extract the rotor angle out from the data. The use of a neural network offers the advantage of robustness to multiple sensor failures and not requiring the transfer function to convert from measured data to rotor angle.

**Anna Winnicki**

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| B.S.: | California Institute of Technology |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Electricity Markets |


## Convex Relaxation-Based Locational Marginal Prices

Anna Winnicki with Advisors Prof. Subhonmesh Bose and Prof. Emeritus Peter Sauer

Supported by the Grainger Foundation

ABSTRACT

We propose and analyze semi-definite relaxation-based locational marginal prices (RLMPs) for real and reactive power in electricity markets. Our analysis reveals that when the non-convex economic dispatch problem has a zero duality gap, the RLMPs exhibit properties similar to locational marginal prices with linearized power-flow equations. Otherwise, they behave similarly to convex hull prices. Restricted to radial distribution networks, RLMPs reduce to second-order cone relaxation-based distribution locational marginal prices. We illustrate our theoretical results on numerical examples. Additionally, we investigate and analyze properties of convex relaxation-based prices to compensate distributed energy resources connected to a radial distribution grid. Our main contribution is the identification of sufficient conditions under which this distribution locational marginal-pricing mechanism supports an efficient market equilibrium and is revenue adequate. We illustrate our analysis through examples.

**Michael Wu**

| | |
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| B.S.: | May 2018, University of Illinois Urbana-Champaign |
| Status: | Working towards M.S. at University of Illinois Urbana-Champaign |
| Professional Interests: | Power Electronics Applications in Consumer Electronics |


## Intelligent IGBT Health Monitoring

Michael Wu with Advisor Prof. Arijit Banerjee

Supported by CRRC China

ABSTRACT

Today, IGBT's have become increasingly popular for their high voltage and current capabilities. These applications range from transport to renewables. However, IGBT's are some of the more delicate components in these high-power systems, and IGBT failure can have severe economic implications. Therefore, it's important to develop an online health-monitoring framework to ensure proper operation of IGBT power modules and to predict the remaining life of a power module. This work aims to create a thermal model of an IGBT power module in a 3-phase, 2-level inverter that can accurately estimate junction temperature. This provides useful information in evaluating the current health and remaining life of a power module. The model will require the development of hardware that can withstand voltages and currents on the order of kilovolts and kiloamps that can accurately measure the on-state saturation voltage and collector current to calculate power dissipation in the power module.

Additional hardware will be developed for the storage of such measurements for fault analysis, which will allow a user the ability to observe various electrical signals at and around the time of failure.

**Jianqiao Xiao**

B.S.: May 2019, University of Illinois Urbana-Champaign

Status: Working towards M.S. at University of Illinois Urbana-Champaign

Professional Interests: Electric Machines with Aerospace Applications

## Multidisciplinary Optimization of Electric Aircraft

Jianqiao Xiao with Advisor Prof. Kiruba S. Haran

Supported by CHEETA

ABSTRACT

I conduct research on an electric machine for aerospace applications from three aspects simultaneously: the mechanical aspect, the aerodynamic co-design aspect and the electrical system aspect. From the mechanical approach, I created CAD models of machines and derived the weight estimation equations for a machine optimization algorithm. For the aerodynamic co-design approach, I modeled the propeller behavior that is to be attached to the electric machine. This model is also fed into the machine optimization algorithm. With the inputs from the mechanical and aerodynamic approaches and the work done by my colleagues, I was also able to start working on system-level optimization of electrified aircraft. I am currently working on combining many individual aspects mathematically and forming the model of a sub-system of such an electric aircraft. In the future, I will continue the system-level optimization. Meanwhile, as the overall design for the electric aircraft changes during optimization, I will continue to perform co-design and mechanical analyses.

**Hanchen Xu**


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| B.S.: | July 2012, Tsinghua University, Beijing, China |
| M.S.: | July 2014, Tsinghua University, Beijing, China |
| Ph.D.: | April 2019, University of Illinois Urbana-Champaign |
| Professional Interests: | Data-driven Control, Grid Data Analytics, Voltage Control |


**Data-driven Voltage Regulation in Radial Power Distribution Systems**


Hanchen Xu with Advisors Prof. Alejandro Domínguez-García and Prof. Emeritus Peter Sauer



Supported by ARPA-E


ABSTRACT


My research focuses on developing a data-driven voltage regulation framework for distributed energy resources (DERs) in a balanced radial power distribution system. The objective is to determine optimal DER power injections that minimize the voltage deviations from a desirable voltage range without knowing a complete power-distribution system model a priori. The nonlinear relationship between the voltage magnitudes and the power injections in the power distribution system is approximated by a linear model, the parameters of which—referred to as the *voltage sensitivities*—can be computed directly using information on the topology and the line parameters. Assuming the knowledge of feasible topology configurations and distribution line resistance-to-reactance ratios, the true topology configuration and corresponding line parameters can be effectively estimated using a few measurement sets on voltage magnitudes and power injections. Using the estimated voltage sensitivities, the optimal DER power injections can be readily determined by solving a convex optimization problem. The proposed framework is intrinsically adaptive to changes in system conditions, such as unknown topology reconfigurations due to its data-driven nature. The effectiveness of the proposed framework is validated via numerical simulations on the IEEE 123-bus distribution test feeder.

**Xuan Yi**

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| B.S.: | May 2014, University of Wisconsin - Madison |
| M.S.: | December 2016, University of Illinois at Urbana-Champaign |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Electrical Machine Design, Transportation Electrification |


## Electro-Thermal Optimization and Validation of High-Frequency Air-Core Permanent-Magnet Motor for Aircraft Application

Xuan Yi with Advisor Prof. Kiruba S. Haran

Supported by Supported by POETS and NASA

ABSTRACT

The current aviation industry demands environmentally friendly and fuel-efficient aircraft to be sustainable. It has been theoretically proven that superconducting machines can power electric airplanes to carry hundreds of people. These machines apply superconducting technology to produce dramatically high-flux density and high-current density, and thus can significantly reduce weight/volume. Conventional machines for aircraft application must reach a power density of eight hp/lb (four times more than the existing state-of-art) to produce similar results. In this project, a non-cryogenic, high-frequency, high-pole-count and high-speed air-core permanent magnet motor is proposed to meet this requirement. In addition, an efficient multi-physics optimization method that can accurately predict electric and thermal performance of such a machine is developed and verified with finite element analysis. Optimum machine sizing is obtained by using a genetic algorithm coupled with an established multi-physics model. The final step will validate the proposed analytical model and optimization method with our 1 MW prototype machine full-power tests at UTRC and POETS facilities.

**Andy K. Yoon**

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| B.S.: | May 2013, University of Illinois at Urbana-Champaign |
| M.S.: | December 2016, University of Illinois at Urbana-Champaign |
| Ph.D.: | July 2019, University of Illinois Urbana-Champaign |
| Professional Interests: | Electric Machines, Electromechanics, Electric Transportation Systems |


**Experimental Validation of High Specific Power Electric Machine**

Andy Yoon with Advisor Prof. Kiruba S. Haran

Supported by NASA

ABSTRACT

A 1-MW electric motor has been designed at a rated speed of 15,000 rpm and has a projected specific power of 13kW/kg. Such a design is appropriate for aerospace applications for its flight-weight and low-volume characteristics. Current plans include experimental validation of the motor assembly to retire thermal, mechanical, electrical, and magnetic risks associated with the design. The testing will take place at Collins Aerospace facility in Rockford. The test facility will allow the device to be tested as a generator up to rated power of 1 MW. The device will also be tested as a motor to study its interaction with a typical aerospace inverter drive.

**Yangxue Yu**

B.S.: May 2018, University of Illinois Urbana-Champaign

Status: Working towards M.S. at University of Illinois Urbana-Champaign

Professional Interests: Electric Machines, Electromechanics, and Electromagnetics

**Mechanical Constraints on High-Speed PM-Assisted Synchronous Reluctance Machine**

Yangxue Yu with Advisor Prof. Kiruba S. Haran

Supported by Johnson Controls International

ABSTRACT

When designing a rotating machine, both the electromagnetic performance and mechanical integrity are important. A good electromagnetic performance gives high efficiency, and satisfaction of mechanical integrity saves the rotor from fracture at high speed. For a permanent magnet-assisted synchronous reluctance machine, the stress concentration is usually located at the center post and bridges of each layer of the magnet slots. A MatLab script was developed to analytically calculate the equivalent stress at the center posts and bridges. The result serves as a check mark of a certain rotor geometry. When the calculated stress is smaller than the threshold, the design can be carried to electromagnetic performance evaluation. Otherwise, the design must be modified to meet the mechanical constraint.

**Xiaolong Zhang**

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| B.S.: | June 2011, Huazhong University of Science and Technology, China |
| M.S.: | June 2014, Huazhong University of Science and Technology, China |
| Status: | Working towards Ph.D. at University of Illinois Urbana-Champaign |
| Professional Interests: | Motor Drives and Control, Permanent Magnet Synchronous Machines, Power Electronics |


## Electromagnetic Losses Analysis in a High-Power, High-Frequency Machine Considering Switching-Supply Harmonics

Xiaolong Zhang with Advisor Prof. Kiruba S. Haran

Supported by NASA and Grainger CEME

ABSTRACT

Electric propulsion has been proposed for large commercial aircraft to reduce fuel use and/or emissions, potentially achieving significant environmental and economic benefits. A high-power, high-frequency permanent magnet synchronous machine drive system is being developed to meet the stringent weight requirements for aircraft applications. The machine employs a multiple-pole, 'iron-less' topology and will be driven by a switched-mode power converter. High magnitude switching harmonics are thus introduced in the machine electric currents and electromagnetic (EM) losses in the copper windings and iron yoke, and rare-earth permanent magnet poles will increase. Analysis and numerical modeling of these switching harmonic losses are crucially important in the machine and drive-system design as the rise in unexpected losses can worsen the internal temperature, stress the insulation material, and degrade the energy efficiency. The harmonic losses are analyzed in a two-step approach. First, a controller-converter motor-drive model is built in MATLAB/Simulink and voltage and current waveforms are obtained and decomposed into spectrum form. Second, a joint-losses computation method based on finite element analysis and analytical formulas are developed to compute the EM losses with those spectrum data as excitation input. The numerically predicted loss numbers will be compared with drive-test results coming soon.

**Madi Zholbaryssov**

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| B.S.: | December 2011, University of Illinois Urbana-Champaign |
| M.S.: | May 2014, University of Illinois Urbana-Champaign |
| Ph.D.: | July 2019, University of Illinois Urbana-Champaign |
| Professional Interests: | Distributed Energy Resources, Microgrids, Distributed Control and Optimization |


## Fast Distributed Optimal Generation Dispatch Over Time-Varying Communication Networks

Madi Zholbaryssov with Advisor Prof. Alejandro Domínguez-García

Supported by ARPA-E NODES

ABSTRACT

The goal of the project is to develop fast distributed algorithms for coordinating the response of distributed energy resources in ac microgrids to minimize electrical line losses and generation cost, and to ensure that the microgrid network constraints are satisfied. The proposed algorithm can be utilized as a tertiary controller for economic optimization of microgrids, or to coordinate distributed energy resources for providing ancillary services to the bulk grid when the microgrid is in grid-connected mode. Such coordination is also required to be resilient against communication delays and random data-packet losses and to have geometric convergence speed, a desirable feature for ensuring fast performance.

**Jeffrey Zhu**

B.S.: May 2017, University of Illinois at Urbana-Champaign

M.S.: May 2019, University of Illinois Urbana-Champaign

Professional Interests: Power system stability and control

**Compensating for the Reduction in Synchronous Inertia Caused by Greater RES Penetration with VSGS**

Jeffrey Zhu with Advisor Prof. Emeritus Peter Sauer

Supported by ECE Indirect Cost Recovery

ABSTRACT

The traditional power grid has been dominated by large synchronous generators, which have offered not only power supply but also frequency stability through their inertia and frequency controls. As more renewable energy sources (RESs), such as wind and solar, are integrated into the grid, they displace synchronous generation units. Many of these RES units do not inherently contribute inertia to the system, so the net effect is a decrease in the aggregate inertia of the power grid. Low inertia threatens the grid with fast frequency dynamics that can trigger under-frequency load shedding or anti-islanding relays in the event of a disturbance. In light of that reality, the frequency support that is traditionally provided by synchronous generators must be found elsewhere. This paper investigates the virtual synchronous generator (VSG) as a solution. The VSG is a controls-based system that mimics the frequency dynamics and response of a synchronous generator. Through simulation, this paper seeks to identify those requirements on the minimum synchronous inertia, virtual inertia, and VSG response time that will maintain the frequency at a safe level and rate of change following a disturbance.

## 7. LABORATORY FACILITIES

The Power Area has assembled some of the nation's finest facilities for experimental and computer-based research and teaching. Both undergraduate and graduate students can take advantage of these facilities.

**The Grainger Power Engineering Software Laboratory** is located in room 4076 ECEB (Electrical and Computer Engineering Building). The Software Laboratory has nine advanced personal computers. All stations are connected to the campus network and Internet.

A major objective of the laboratory is to develop an extensive library of commercial software and large-scale databases for power area applications. Software is based on Windows 10. Some of the commercial software packages currently in use include:

- Mathematica / Wolfram (advanced symbolic mathematics, fully integrated technical computing)
- Mathcad / PTC (industry standard for engineering calculations)
- MATLAB / MathWorks (MATrix LAB, technical computing)
- Simulink (Matlab package, graphical simulation, model-based design, dynamic and embedded)
- SimElectronics (Simulink Toolbox, model and simulate electronic and electromechanical systems)
- SimPowerSystems (Simulink Toolbox, modeling and simulating electric power systems)
- xPC Target (Simulink, rapid control prototyping and hardware-in-the-loop)
- PLECS (Simulink, fast simulation of electrical and power electronic circuits)
- acslX(treme) / AEgis (general-purpose simulation environment)
- LabVIEW (visual programming language, lab bench dynamometer control program & Gui)
- PSS/E / Siemens PTI (power system simulator for engineering, electrical transmission)
- RISKSYM / Henwood (package for energy market analysis)
- PowerWorld (power systems analysis, power market analysis, locational marginal price analysis)
- Power System Tool Box (PST Version 2.0)
- ANSYS / Ansoft (finite element analysis modeling)
- Maxwell (ANSYS, EM Field Simulation for high-performance electromechanical design)
- RMxprt (ANSYS, design software for electric machines)
- Simplorer (ANSYS, simulation of electrical, electromechanical, electromagnetic, power, thermal)
- Flux / Magsoft / Cedrat (electromagnetic and thermal physics simulation)
- Eagle / CadSoft (schematic capture and PCB design)
- SAM / NREL (System Advisor Model, PV Photovoltaic system cost estimation)
- Altera Quartus & DSP Builder (FPGA software & Digital Signal Processing tool)
- SPEED / STAR-CCM+ / CD-adapco / Siemens (design and analysis of electric machines)

A secondary objective of this laboratory is the use of this space as a controller hardware-in-the-loop (C-HIL) testbed. The C-HIL testbed is used to achieve: (1) high-fidelity modeling and real-time simulation of an electric power grid, (2) the synthesis of coordination and control algorithms on several controller hardware platforms, and (3) the testing and validation of the resulting coordination and control technologies. The electric power grid is modeled using the Typhoon HIL Platform, and the Arduino Due and National Instruments cRIO controller hardware platforms are employed in the testbed. The hardware that comprises this testbed includes:

- A set of Arduino Due microcontrollers, each coupled with a W5100 Ethernet shield and XBee module
- One Typhoon HIL 402 unit
- Three Typhoon HIL 603 units
- A National Instruments cRIO 9068 with NI PS-15 power supply
- Two 24 Port Gigabit Switches

This comes with a set of software packages installed on two advanced personal computers as listed below:

- Arduino IDE Software
- Processing 3.3.7
- LabVIEW 2017
- Typhoon HIL testing software
- MATLAB R2017a

**The Grainger Electrical Machinery Laboratory** is located in 4024 ECEB (Electrical and Computer Engineering Building). This facility is primarily for undergraduate teaching and is used for ECE 431 (Electric Machinery), ECE 469 (Power Electronics), and Engineering Open House (EOH) Power and Energy demonstrations. With many power and energy teaching labs cutting back on hardware and machines, or going totally to software or virtual experiments, the Grainger lab has been able to maintain and increase our large inventory of test machines and equipment. Ten self-contained machinery workstations are available. Each has a two-horsepower machine set with a servo-based dynamometer. The lab benches were updated with new equipment for the academic year (2013 - 2014) including new digital wattmeters, oscilloscopes, signal generators, power supplies, and speed/torque displays. The equipment is suitable for the study of induction, synchronous, and dc machines. Small portable machine sets are used to introduce stepper motors and brushless dc machines. Transformers, resistor boxes, capacitor boxes, SCR, and power FET units are provided to support a full range of experiments in all aspects of power and power electronics. The facility has a dedicated three-phase supply 120/208 Vac (150 kVA) and 240 Vdc (+/- 120 Vdc) 80 A rectifier. In 2015, we added a new set of synchronous machines.

The Power and Energy Systems group has Advanced Power Applications Labs in 4020 and 4026 ECEB. These research labs have motor test benches with precision dynamometers and a third new high-horsepower test bed. The benches can access 208 Vac 3-phase, 480 Vac 3-phase, and 240 Vdc. These labs serve as a research facility for all hardware aspects of power electronics, machines, and power systems. Additional equipment is available for the study of harmonic effects, high-performance switching converters, and digitally controlled converters/drives. Computers are available throughout the laboratory for automation of experiments using LabVIEW and Matlab/Simulink/Real-Time Toolbox. This fourth-floor lab has direct access to the roof to allow for solar panel, wind turbine, and weather station placement.

## 8. DIRECTORY

### THE UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
### COLLEGE OF ENGINEERING


Rashid Bashir, Dean
(217) 333-2150
rbashir@illinois.edu

Philippe Geubelle, Executive Associate Dean
(217) 244-7648
geubelle@illinois.edu

Dale Wright, Associate Dean for Advancement
(217) 244-0604
dlwright@illinois.edu

Michael J Devocelle, Associate Dean for Finance and Administration
(217) 333-2151
mdevocel@illinois.edu

Jennifer Bernhard, Director, Applied Research Institute
(217) 333-0293
jbernhar@illinois.edu

Jonathan Makela, Associated Dean for Undergraduate Programs
(217) 333-2280
ravaioli@illinois.edu

Harry Dankowicz, Associate Dean for Graduate, Professional and Online Programs
(217) 244-1231
danko@illinois.edu

Address: University of Illinois College of Engineering
306 Engineering Hall
1308 W. Green St
Urbana, IL 61801
Fax: (217) 244-7705
www.engr.illinois.edu

## DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING ADMINISTRATION

Bruce Hajek, Department Head
(217) 333-3605
b-hajek@illinois.edu

Michael Oelze, Associate Head Graduate Affairs
(217) 333-9226
oelze@illinois.edu

Erhan Kudeki, Associate Head for Undergraduate Affairs/Chief Advisor
(217) 265-0128
erhan@illinois.edu

Catherine Somers, Assistant Head for Administration
(217) 244-1783
csomers@illinois.edu

Heather Vazquez, Senior Director of Advancement
(217) 333-2517
hfv@illinois.edu

Nikki Slack, Alumni and Donor Relations Coordinator
(217) 265-4317
nslack@illinois.edu

Address:

University of Illinois at Urbana-Champaign
Department of Electrical and Computer Engineering
Electrical and Computer Engineering Building
306 N. Wright Street, MC-702
Urbana, IL 61801

## POWER AND ENERGY SYSTEMS AREA

Robin Smith, Office Manager
(217) 333-6592
rsmth@illinois.edu

Joyce Mast, Coordinator
Grainger Center for Electric Machinery
and Electromechanics
(217) 265-5128
jmast@illinois.edu

Prof. Emeritus Peter W. Sauer
Director of the Power Affiliates Program
(217) 333-0394
psauer@illinois.edu

Prof. Arijit Banerjee
(217) 300-5319
arijit@illinois.edu

Prof. Subhonmesh Bose
(217) 244-2101
boses@illinois.edu

Prof. Alejandro Domínguez-García
(217) 333-3953
aledan@illinois.edu

Prof. George Gross
(217) 244-1228
gross@illinois.edu

Prof. Kiruba Haran
(217) 244-1838
kharan@illinois.edu

Prof. Emeritus Philip T. Krein
(217) 333-4732
mapai@illinois.edu

Prof. Emeritus M.A. Pai
(217) 417-9725
krein@illinois.edu

Prof. Andrew Stillwell
(217) 300-7400
andrews@illinois.edu

Prof. Richard Zhang
(217) 300-6912
ryz@illinois.edu

Kevin Colravy, Research Engineer
(217) 333-1056
colravy@illinois.edu

Address: University of Illinois at Urbana-Champaign
Department of Electrical and Computer Engineering
Electrical and Computer Engineering Building
306 N. Wright Street, MC-702
Urbana, IL 61801
Fax (217) 333-1162
www.energy.ece.illinois.edu

**AMEREN**

Mr. George Mues
Ameren Services
1901 Chouteau Avenue
P.O. Box 66149
St. Louis, MO 63166
Gmues@ameren.com

**CITY WATER, LIGHT AND POWER, SPRINGFIELD, IL**

Mr. Shaun Anders
City Water, Light and Power
1008 E. Miller Street
Springfield, IL 62702
(217) 789-2120
Shaun.Anders@cwlp.com

**CONTINENTAL AUTOMOTIVE**

Mr. Dennis Stephens
21440 Lake Cook Road
Deer Park, IL 60010
(847) 862-2757
dennis.stephens@continental-corporation.com

**ELECTRICAL MANUFACTURING AND COIL WINDING ASSOCIATION, INC.**

Mr. Charles E. Thurman
EMCWA
P.O. Box 278
Imperial Beach, CA 91933
(619) 575-4191
cthurman@emcwa.org

**EXELON**

Ms. Jennifer Sterling
Exelon
Two Lincoln Centre
Oakbrook Terrace, IL 60181
(630) 437-2764
jennifer.sterling@exeloncorp.com

Mr. Tom Kay
Exelon
Two Lincoln Centre
Oakbrook Terrace, IL 60181
(630)437-2758
thomas.kay@exeloncorp.com

**FLANDERS, INC.**

Mr. Stan Mann
Flanders Electric
8101 Baumgart Rd.
Evansville, IN 47725
smann@flanderselectric.com

**G&W ELECTRIC**

Mr. John T. Pederson
G&W Electric Company
305 W. Crossroads Pkwy
Bolingbrook, IL 60440
jpederson@gwelec.com

Mr. James Parejko
G&W Electric Company
305 W. Crossroads Pkwy
Bolingbrook, IL 60440

**MIDAMERICAN ENERGY COMPANY**

Mr. Richard W. Polesky
MidAmerican Energy
One River Center Place
106 E. Second Street
P.O. Box 4350
Davenport, IA 52801
(319) 333-8187
rupolesky@midamerican.com

**POWERWORLD CORPORATION**

Dr. Mark Laufenberg
PowerWorld Corporation
2001 S. First Street
Champaign, IL 61820
(217) 384-6330
lauf@powerworld.com

Dr. James Weber
PowerWorld Corporation
2001 S. First Street
Champaign, IL 61820
(217)384-6330
weber@powerworld.com

**S&C ELECTRIC COMPANY**

Dr. Michael G. Ennis
S&C Electric Company
6601 North Ridge Boulevard
Chicago, IL 60626-3997
(773) 338-1000
mennis@sandc.com

**SARGENT & LUNDY ENGINEERS**

Ms. Carol Talaronek
Sargent & Lundy Engineers
55 East Monroe Street
Chicago, IL 60603
(312) 269-3578
caroltalaronek@sargentlundy.com
Or contact
Linda Kelnosky
linda.e.kelnosky@sargentlundy.com

Mr. Robert M. Dahlgren
Sargent & Lundy Engineers
55 East Monroe Street
Chicago, IL 60603
robert.m.dahlgren@sargentlundy.com

**PROFESSOR EMERITUS M.A. PAI**

Prof. Emeritus M. A. Pai
33 Rockwood
Irvine, CA. 92614
mapai@illinois.edu

## 9. REFERENCES AND PUBLICATIONS


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