Final Report for the NSF Workshop on Power Electronics-enabled Operation of Power Systems

NSF Award No.: 1933207

PI: Qing-Chang Zhong, Illinois Institute of Technology

Venue: Illinois Institute of Technology, Chicago, IL

Date: October 31 - November 1, 2020

Organizing Committee

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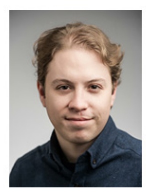

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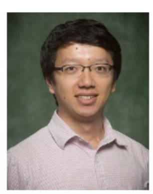

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1 Introduction

Power systems worldwide are going through a paradigm shift. Millions of distributed energy resources (DER) are being connected to power systems imposing unprecedented challenges to grid stability, reliability, security, and resiliency. The fundamental challenge behind this paradigm shift is that future power systems will be power electronics-based, instead of electric machines-based, with a huge number of active, intermittent, non-synchronous, and heterogeneous players.

The objective of this NSF workshop was to bring experts from control systems, power electronics, and power systems together to: i) identify fundamental challenges and needs in multidisciplinary research and education in control of power electronics-enabled power systems for enhanced grid stability, autonomy, scalability, operability, reliability, security, and resiliency; ii) strengthen collaborative efforts to tackle the challenges identified; and iii) raise the awareness of funding agencies and policy-makers to support and nurture research and educational activities in advancing fundamental knowledge, enabling technologies, and workforce development in this area.

A total of 134 participants from funding agencies, regulatory commissions, utilities, think-tanks, vendors, and universities etc. registered to attend the workshop. A group photo taken on the first day is shown below.

Figure 1 Group photo of the participants taken on the first day of the workshop.

2 Organization Process

Upon the award of the workshop grant, the PI had several meetings with the NSF Energy, Power, Control, and Networks (EPCN) program directors (Anil Pahwa, Radhakishan Baheti, Alireza Khaligh, Anthony Kuh) to finalize the organizing committee, speakers, and other details. Then, the Organizing Committee started working on the logistics for the workshop.

A guiding philosophy in organizing the workshop was to widen the participation and encourage diversity and equality. The workshop was announced through multiple channels, such as the IEEE Control Systems Society E-letter, conferences and LinkedIn, and the response was overwhelming. For example, the LinkedIn post quickly received 1980 views, as shown in Figure 2. Financial support was offered to faculty in need. All early-stage faculty members were offered financial support to attend the workshop upon request.

Figure 2 LinkedIn post announcing the workshop.

The workshop was committed to fostering an environment in which all members of the community are safe, secure, and free from sexual harassment of any form. The policies that address sexual harassment, other forms of harassment, and sexual assault, and that includes clear and accessible means of reporting violations of the policies were explicitly promoted.

3 Workshop Program

The workshop was scheduled for two days. The Vice Provost for Research of IIT, Dr. Fred J. Hickernell, warmly welcomed all participants. Dr. Anil Pahwa from NSF opened the workshop with a talk entitled "NSF Perspectives: Challenges and Opportunities," followed by 10 keynotes, 9 short talks, and 2 panel discussions. The participants also visited the IIT Microgrid and the SYNDEM Smart Grid Lab. The detailed program is shown below.

Thursday Oct 31

08:30-09:00	Registration and Continental Breakfast
09:00-09:05	Opening and Logistics, Qing-Chang Zhong, Illinois Institute of Technology (IIT)
09:05-09:10	Welcome Remarks, Fred J. Hickernell, Vice Provost for Research, IIT
09:10-09:15	NSF Opening Remarks, Anil Pahwa, National Science Foundation (NSF)
09:15-10:30	Session 1 (Chair: Mohammad Shahidehpour, IIT)
09:15	NSF Perspectives: Challenges and Opportunities, Anil Pahwa, Alireza Khaligh, Radhakisan S. Baheti, and Anthony Kuh, NSF
09:30	Enabling a Power Electronics Grid, Deepak Divan, Georgia Institute of Technology
10:00	Power Electronics-enabled Autonomous Power Systems: Synchronized and Democratized (SYNDEM) Smart Grids, Qing-Chang Zhong, IIT
10:30-11:00	Networking; Coffee/tea
11:00-12:30	Session 2 (Chair: Alex Flueck, IIT)
11:00	Optimizing Ubiquitous Power Electronics for the Future Power Grid, Zhenyu (Henry) Huang, Pacific Northwest National Laboratory
11:30	Technical Challenges of High Level of Inverter-based Resources in Power Grids, Robert Lasseter, University of Wisconsin - Madison
12:00	Research & Education in CURENT on Power Electronics for Power Systems, Fred Wang, The University of Tennessee, Knoxville
12:30-13:30	Group Photo; Networking Lunch
13:30-15:00	Session 3 (Chair: John Z. Shen, IIT)
13:30	Growing Deployment of Power Electronics in Power Systems: Challenges, Opportunities, and Research Initiatives, Abraham Ellis, Office of Electricity, Department of Energy
14:00	Flexible Division and Unification Control Strategies for Resilience Enhancement in Networked Microgrids, Mohammad Shahidehpour, IIT
14:30	Medium Voltage Power Electronics Technology, Alex Huang, UT Austin
15:00-15:30	Networking; Coffee/tea
15:30-16:15	Session 4 (Chair: Ian Brown, IIT)
15:30	Protection of High-Voltage DC Transmission Systems, Maryam Saeedifard, Georgia Institute of Technology
15:45	Grid-Forming Photovoltaic Inverter: Opportunities and Challenges, Hariharan Krishnaswami, Department of Energy
16:00	The Advanced Grid Innovation Lab for Energy - A Collaborative Program of the New York Power Authority, George Stefopoulos, New York Power Authority
16:15-17:00	Session 5 (Chair: Sairaj Dhople, University of Minnesota)
	Panel Discussions: Fundamental Challenges and Research Needs
17:00-18:00	Tour: IIT Microgrid and SYNDEM Smart Grid Lab

Friday Nov 1

08:30-09:00	Registration and Continental Breakfast
09:00-10:30	Session 6 (Chair: Zuyi Li, IIT)
09:00	Power Engineering Education in the Age of Climate Crisis – A Holistic View, Ned Mohan, University of Minnesota
09:30	Power Electronics in Transportation Electrifications, Ali Emadi, McMaster University
10:00	Microgrid Testbeds at Different Scales for Research and Education, Beibei Ren, Texas Tech University
10:15	Resilient Architectures and Algorithms for Generation Control of Inertialess AC Microgrids, Alejandro Dominguez-Garcia, UIUC
10:30-11:00	Networking; Coffee/tea
11:00-12:00	Session 7 (Chair: Mahesh Krishnamurthy, IIT)
11:00	Nonlinear Decentralized Control for Future Grids, Brian Johnson, University of Washington
11:15	Multi-Scale Control of Power Electronics for Power Systems, Sudip K Mazumder, University of Illinois, Chicago
11:30	High Frequency Power Electronics at the Grid Edge: Opportunities and Challenges, Minjie Chen, Princeton University
11:45	Impedance-Based Evaluation of Stability Impacts of Inverter-Based Resources, Shahil Shah, NREL
12:00-12:45	Session 8 (Chair: Zi-Ang John Zhang, Binghamton University) Panel Discussions: Potential Approaches and Directions
12:45-12:50	Concluding Remarks
12:50-13:30	Networking Lunch
13:30-14:30	Tour: IIT Microgrid and SYNDEM Smart Grid Lab / Farewell

4 Panel Discussions

4.1 Panel 1: Fundamental Challenges and Needs

Chair: Sairaj Dhople, University of Minnesota

Panelists: Anil Pahwa, National Science Foundation (NSF); Deepak Divan, Georgia Institute of Technology; Qing-Chang Zhong, Illinois Institute of Technology (IIT); Zhenyu (Henry) Huang, Pacific Northwest National Laboratory; Robert Lasseter, University of Wisconsin - Madison; Fred Wang, The University of Tennessee, Knoxville; Abraham Ellis, Office of Electricity, DOE; Mohammad Shahidehpour, Illinois Institute of Technology (IIT); Alex Huang, UT Austin; Maryam Saeedifard, Georgia Institute of Technology; Hariharan Krishnaswami, Department of Energy; George Stefopoulos, New York Power Authority.

The focus of this panel session was to highlight fundamental challenges and identify research needs for power networks with high penetration of power-electronics circuits. The conversation essentially boiled down to bottom-up concerns (i.e., focusing on the power-electronics interfaces themselves) and top-down considerations (i.e., focusing on power-system operations). A brief overview of major discussion points is provided below:

- Cybersecurity of the future network with potentially millions of inverters is an important consideration. This is particularly important given the fact that we will likely see a future where over-the-air updates of inverter controls and communication between inverters are anticipated to be commonplace. In such a future, there should be emphasis on graceful degradation of operation in the face of attacks, validation of proof-of-concept ideas through dedicated testbeds, and impact assessment of cyber-layer attacks and vulnerabilities on bulk grids.
- Ancillary services from power-electronics circuits were recognized to be an integral part of the future power network. That said, it was recognized that legacy notions that were relevant in a network dominated by synchronous generators may have to be revisited and modified in a future network with dominantly electronics-heavy generation and consumption.
- Aggregated operation of millions of devices will require attention. Ensuring stable operation in a landscape where communication networks and standards are constantly in flux is challenging. Endowing autonomy to power electronics interfaces will be key.

4.2 Panel 2: Potential Approaches and Directions

Chair: Ziang Zhang, Binghamton University - SUNY

Panelists: Ali Emadi, McMaster University; Beibei Ren, Texas Tech University; Alejandro Dominguez-Garcia, UIUC; Brian Johnson, University of Washington; Sudip K Mazumder, University of Illinois - Chicago; Minjie Chen, Princeton University; Shahil Shah, NREL.

The objective of this panel session was to share thoughts on future research directions. Discussion was focused on appropriate modeling modalities to bridge the gap between power electronics and power system dynamics, the power systems perspective of new inverter capabilities, and potential ways to foster collaborations between the power systems and power electronics communities. Summary of major discussions is provided below:

- Modeling: The panel agreed that existing models at different time scales are still needed for future research. The panel suggested a few efforts that could shorten the gaps such as create a standardized testing interface (e.g., the interaction between the RF and circuits communities), link different simulations tools with script interfaces (e.g., the electrical vehicle community). Cross validation between different models were identified to be necessary.

- Collaboration : Engineering the future electric grid will require bottom-up and top-down perspectives. Research in power electronics can provide enabling technologies for the future power grid, however, there is a need for more collaboration between the two communities. Power systems researchers need to understand the low-level details of power electronics; power electronics researchers need to understand how bulk power systems operate and why it operates in the current fashion.
- Standards: New power electronic converters have to be compatible with existing grid features such as droop and self-synchronization. Standard models with clearly defined input-output of inverters are needed for detailed testing and analysis with the grid.
- Validation and field demonstration: While numerical simulations are important to understand how system works, it is important to carry out experiments in the lab and demonstrations in the field before large-scale deployment.

In addition to the power systems applications, a few other questions regarding the electrification of passenger vehicles and aircrafts were raised. The panel concurred that there are similarities among those applications, but the technical challenges might be different in terms of functionality, cost, mechanical, and thermal perspectives.

5 Lab Tours

5.1 IIT SYNDEM Smart Grid Lab

The IIT SYNDEM Smart Grid Lab is equipped with state-of-the-art research facilities, such as a 12-converter SYNDEM smart grid testbed, a wind power system equipped with a permanent magnet synchronous generator (PMSG), a doubly-fed induction generator (DFIG), and an squirrel-cage induction generator (SCIG) , a solar power system, a storage system, a modular multi-level converter, and a large-scale real-time simulator with the support from the NSF Major Research Infrastructure (MRI) program under award No. 1828541. More details of the lab can be found at http: http://peac.iit.edu/.

The workshop participants toured the lab facilities and were briefed with the latest research activities and outcomes. A photo of the tour is included on the next page in Figure 3.

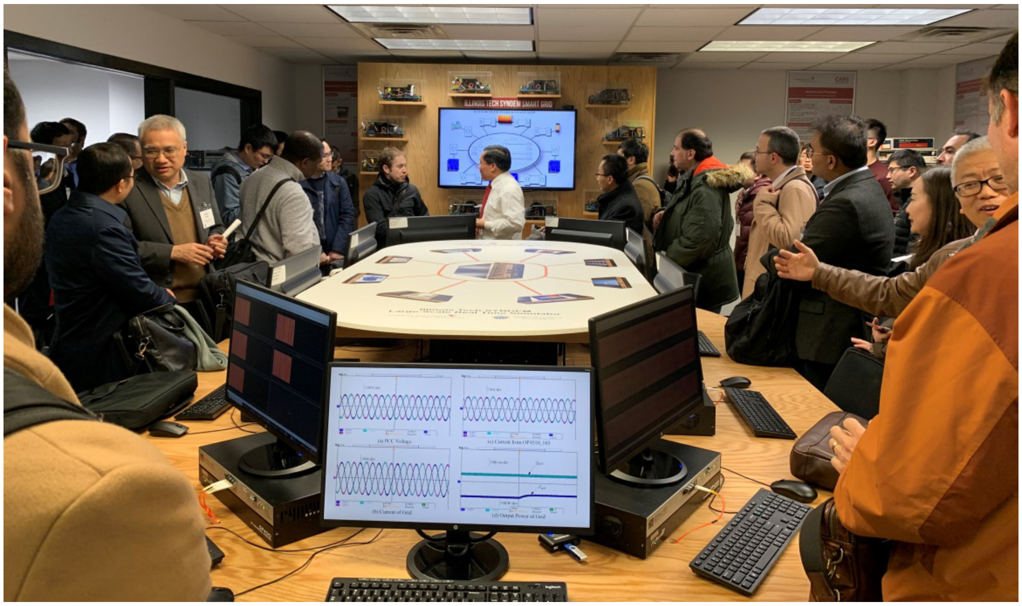

Figure 3 Participants touring the IIT SYNDEM Smart Grid Lab.

5.2 IIT Microgrid

Under the leadership of Dr. Mohammad Shahidehpour, IIT developed the nation's first Perfect Power microgrid. The $14 million project has equipped IIT's distribution system with enhanced reliability, new sustainable energy sources (roof-top solar panels, wind generation units, flow batteries and charging stations for electric vehicles), and smart building automation technology (building controllers, Zigbee sensors, controllable loads) for energy efficiency and demand response. Participants also toured the IIT Microgrid; see Figure 4.

Figure 4 Participants touring the IIT Microgrid.

6 Challenges and Needs Identified

6.1 Large Scale and Heterogeneity

Power systems are already regarded as the largest man-made system in the world but the scale of power systems is still growing. The replacement of large centralized power plants with small distributed generators greatly increases the scale of power systems. Also, the heterogeneity of power systems increases as different types of distributed generators and loads equipped with different controllers are introduced into power systems. Moreover, the fast advancement of technologies in computation, PV solar, wind, EV, power semis, storage, microcontrollers, sensors, IoT, communication technologies, online services, social media, mobile pay, block-chain, cloud, deep learning, etc., further complicates the landscape.

6.2 Modelling

The increasing scale and heterogeneity of power systems immediately bring another challenge – modelling of power systems. Millions of devices that belong to different physical domains, have different dynamics on widely different time scales, from microseconds for power electronic switching, milliseconds for grid interaction, seconds for grid control, up to hours for thermal storage in buildings and large refrigeration systems.

6.3 Control and Stability

It is well known that when stable devices are connected together the resulting system may be unstable. This is certainly true for future power systems with millions of heterogeneous devices from many different vendors. It is a great challenge to develop holistic control algorithms so that future power systems can provide frequency response, voltage response, oscillation damping, and fault protection etc. Moreover, foundational capabilities that can monitor fast dynamics beyond phasors on the system level and can model systems with higher resolutions and wider bandwidth are needed. Grid-level stability issues have to be addressed in the context of decentralized and hierarchical control algorithms that can be implemented on power electronics devices on the grid edge. Furthermore, the structure of bulk power systems is changing continually, so the control algorithms will have to be able to maintain stable operation under structural changes of power systems and even grid faults.

6.4 Simple Rules for Complex Power Systems

Power systems are very complex cyber-physical systems. Their management and operation can be indeed very challenging. Are there simple rules available for power systems to manage themselves with minimal human intervention and with minimal reliance on information and communication technology (ICT) infrastructure? In other words, is it possible to achieve autonomous operation for power systems? Questions like whether distributed generators should be managed by systems operators need to be answered.

6.5 Efficient, Reliable, and High-density Power Electronic Converters

Future power systems will no longer be electric machines based but power electronics based. Power electronic converters are building blocks for future power systems. It is critical to study, develop and manufacture efficient, reliable, high-density power electronic converters. While there are many topologies available, there is a need to identify and integrate the best topologies suitable for power systems applications. It becomes imperative to standardize and modularize power electronic converters for different applications. Another challenge along this line the availability of high-frequency, high-power, and high-voltage power semiconductor devices, such as wideband-gap devices.

6.6 Cybersecurity

Introducing ICT infrastructure into power systems is what makes power systems smart. While this brings tremendous benefits to operators and users of power systems, it also brings unprecedented challenges to power systems in the context of cybersecurity. There is no longer a need to be physical close to critical assets of power systems to cause damage or large-scale blackouts. Another challenge that is often neglected is that ICT systems are themselves very large and the adoption of ICT systems into power systems is not straightforward. Package losses and transmission delays are two very common problems.

6.7 Education

The next generation of power engineers must be trained in key subject areas to facilitate the realization of power-electronics-enabled grids. This will require a restructuring of power engineering curricula so that relevant aspects of power systems, power electronics, and control systems topics are cross-fertilized, and students are equipped with fundamental concepts and skills in these areas. For instance, students that specialize in power electronics must gain a working understanding of frequency dynamics and bulk power systems and power systems engineers should be exposed to basic models of power electronic converters and their physical characteristics. Moreover, control and systems theory is a fundamental enabler for future power systems, and there is a need to strengthen the control and systems curricula in this context. Ideally, next-generation power engineers should be experts in conventional power systems, power electronics, and control engineering. Hardware skills are critical for next-generation power engineers and are even more important now during the global trend of moving towards software.

7 Potential Approaches and Directions

7.1 Architecture

Future system architectures must be carefully designed so that various control functions are appropriately partitioned across spatial and temporal scales. Centralized control architectures are no longer suitable for future power systems and distributed/decentralized control architectures are emerging as a logical alternative. How to maintain system-level stability without a central controller is a fundamental question to be answered when determining the architecture for future power systems. For instance, fast-acting power electronic converters will take decentralized control action at the individual converter level to ensure system stability whereas networked system-wide controllers must ensure energy balance over extended time horizons and larger geographical regions. Such an approach closely mirrors the current systems where machines dictate instantaneous dynamics and system-wide controllers ensure frequency restoration and economic operation. With respect to next-generation system-level controllers, a variety of communication and control architectures have been put forth to realize power networks dominantly composed of power electronics circuits. For the particular case of low-inertia ac microgrids, distributed architectures have the obvious advantages of ensuring that control methods can be realized without global knowledge and guaranteeing resiliency to faults. The Synchronized and Democratized (SYNDEM) grid architecture is one such example. It is a distributed control architecture that unifies the integration of conventional generators, emerging distributed generators, and active loads with the synchronization mechanism of synchronous machines. It does not rely on ICT for device-level control, so the bandwidth of the ICT infrastructure needed is reduced and concerns surrounding cybersecurity are reduced congruently.

7.2 Virtual Synchronous Machines

The challenge of scale and heterogeneity faced by future power systems presents a compatibility threat to power systems. Current power systems are dominated by electric machines, i.e., synchronous generators on the generation side and induction machines on the demand side. Synchronization is the fundamental rule of law that has governed the stable operation of power systems for over 100 years. It is critical to continue adopting this fundamental rule of law to govern future power systems to ensure backward compatibility. Virtual synchronous machines (VSM) are power electronic converters that are controlled to behave as conventional synchronous machines. With the VSM technology, millions of distributed generators and active loads can take part in the regulation of system frequency and voltage, without relying on ICT at the device level for control. This can ensure a smooth transition from the current power system paradigm dominated by electric machines to the future power system paradigm dominated by power electronic converters. Some other approaches, mainly under a more generic term referred to as grid-forming inverter control (see below), can also address the compatibility problem to some extent but there is a need to study whether the underlying mechanisms are compatible with the overarching need for synchronization and synchronous operation.

7.3 Grid-forming Inverters

The term grid-forming is emerging as a popular term. The potential of grid-forming inverters in ensuring stability in future grids is, by now, well documented through a variety of studies. While grid-following inverters are unable to provide frequency support, grid-forming inverters can potentially improve power quality and system resiliency in a future network with limited inertia. There is a need to characterize what is meant by grid-following and grid-forming inverters, although admittedly, this may be a difficult undertaking given the vast number of manufacturers, vendors, and lack of standardization of design and control practices. That said, there is a general acceptance that grid-following inverters are those where frequency is measured and assumed to be fixed by the external system, while grid-forming inverters are essentially controlled voltage and frequency sources. Regarding open questions, it is quite clear that this is a problem of scale. Small networks of grid-forming inverters can be finely tuned, modeled, and analyzed; however, system design, protection, modeling, and control (across timescales) for large networks of grid-forming inverters is an open research direction. Moreover, as mentioned above, the underlying mechanism that guarantees the compatibility of grid-forming inverters with power systems needs to be further studied.

7.4 Impedance-based Modelling

Several innovative modeling paradigms have been proposed for power networks with high levels of power-electronics circuits. A particularly useful and relevant approach is impedance-based modeling. This general strategy addresses two concerns: i) the high level of diversity in power-electronics control methods, and ii) the limited availability of perfect high-fidelity models. Impedance-based methods have been applied to a variety of settings including wind turbines, power-system stabilizers, HVDC transmission, etc. There is a possibility that with this approach, one would be able to standardize controls, models, and analysis methods for future power systems with limited inputs on precise models and parameters that manufacturers may be unwilling to share.

7.5 High-frequency Converters

The demand for efficient, reliable, and high-density power electronic converters requires holistic thinking about power electronic converters from the perspectives of materials, components, devices, and systems. The advent of wide-bandgap power semiconductors has extended the feasible operating regimes of power converters to increasingly high-voltage, high-power, high-temperature and high-frequency applications, all of which are needed for future power systems. In addition to well-known benefits that wide-bandgap devices provide toward reduced passive component sizing, higher efficiency, reduced costs, and operation in harsh environment, it is apparent that they also enable controllers with enhanced performance and extended bandwidth. Research is needed to quantify possible improvements in control performance metrics and address potential issues in sensor design, embedded implementations, volatile output terminal dynamics, switch-level modulation, modular topologies etc. A cross-cutting investigation of such issues will ensure that high-frequency converters can be fully utilized to enable the paradigm shift for power systems.

7.6 Testbeds

Field demonstrations and laboratory testbeds are critical in validating technologies before large-scale deployment. Aspects such as frequency control, voltage control, ancillary services provisioning, asset scheduling, and other functions of power electronic converters have been demonstrated in laboratories with hardware set-ups at different scales and with computational real-time simulations such as Hardware-in-the-Loop simulations. While real-time simulators are easy to set-up, there are concerns about the accuracy, cost, and numerical instability. Some directions for future research include networking multiple microgrids, establishing testbeds and field demonstrations at a large scale with physical power electronic converters, and investigating the role of ICT infrastructure.

7.7 Solid-State Power Flow Control

Solid-State Transformers (SST) refer to power electronic converters equipped with high-frequency transformers, which are intended to replace transformers at 50 Hz or 60 Hz. Due to the potential technological and economic impact, different types of medium-voltage SST have been extensively developed because the medium voltage (up to 69kV) distribution grid is the interface between bulk transmission grid and the secondary distribution grid. This provides a potential means to manage faults and power flow.

While fully-rated SST is becoming a potential option, it may be more economical to adopt hybrid power transformers that incorporate a fractionally-rated converter with a conventional transformer.

It is also possible to replace conventional substations with Solid State Power Substations (SSPS), which house multiple modular-based power electronics converters (SSTs for example). The end goal is to develop a scalable, adaptable, cost-effective power transmission and distribution network that spans multiple voltage levels. The power electronics modules in such systems can be placed in series or in parallel to provide different power ratings with minimum design changes required for control and communications.

8 Dissemination and Outreach

The PI submitted a news article to IEEE Power Electronics Magazine after the workshop and it was accepted and published in the March 2020 issue. A copy is included in Fig. 5.

Happenings

by Qing-Chang Zhong

Power Electronics-Enabled Operation of Power Systems

Power systems are going through a paradigm shift as millions of distributed energy resources are connected to the grid worldwide. This imposes unprecedented challenges to the operation of future power systems, which will be power electronics based instead of electric machines with millions of active, intermittent, nonsynchronous, and heterogeneous players. It is important to identify the fundamental challenges and needs in multidisciplinary research and education in the control of power electronics-enabled power systems for enhanced grid stability, autonomy, scalability, operability, reliability, security, and resiliency, while strengthening collaborative efforts to tackle these issues and raise awareness within funding agencies and among policy makers. To help do so, the Energy, Power, Control, and Networks Program of the U.S. National Science Foundation (NSF) sponsored a workshop, Power Electronics-Enabled Operation of Power Systems, at the Illinois Institute of Technology (IIT), Chicago, from 31 October to 1 November 2019, under award 1933207.

The workshop's organizing committee included Prof. Qing-Chang Zhong (chair), IIT; Prof. Sairaj Dhople, University of Minnesota; Prof. Brian Johnson, University of Washington; Prof. Beibei Ren, Texas Tech University; Dr. Thanh Long Vu, Pacific Northwest National Laboratory; Prof. Ziang Zhang, Binghamton University; and Annette Lauderdale, IIT.

More than 130 participants from funding agencies, regulatory commissions, utilities, national labs, universities, and vendors attended (Figure 1). The vice provost for research at IIT, Prof. Fred J. Hickernell, welcomed them. Dr. Anil Pahwa from the NSF kicked off the workshop with "NSF Perspectives: Challenges and Opportunities," followed by 10 keynotes, nine short talks, and two panel discussions. The participants also visited the IIT microgrid and the SYNDEM Smart Grid Lab.

The talks included

- "Enabling a Power Electronics Grid," Prof. Deepak Divan, Georgia Institute of Technology
- "Power Electronics-Enabled Autonomous Power Systems: Synchronized and Democratized (SYNDEM) Smart Grids," Qing-Chang Zhong, IIT
- "Optimizing Ubiquitous Power Electronics for the Future Power Grid," Dr. Zhenyu Henry Huang, Pacific Northwest National Laboratory
- "Technical Challenges of High Level of Inverter-Based Resources in Power Grids," Prof. Robert Lasseter, University of Wisconsin–Madison
- "Research and Education in CURENT on Power Electronics for Power Systems," Prof. Fred Wang, University of Tennessee, Knoxville
- "Growing Deployment of Power Electronics in Power Systems: Challenges, Opportunities, and Research Initiatives," Dr. Abraham Ellis, U.S. Department of Energy
- "Flexible Division and Unification Control Strategies for Resilience Enhancement in Networked Microgrids," Prof. Mohammad Shahidehpour, IIT
- "Medium-Voltage Power Electronics Technology," Prof. Alex Huang, University of Texas at Austin
- "Power Engineering Education in the Age of Climate Crisis: A Holistic View," Prof. Ned Mohan, University of Minnesota
- "Power Electronics in Transportation Electrifications," Prof. Ali Emadi, McMaster University.

The short talks were

- "Protection of High-Voltage dc Transmission Systems," Prof. Maryam Saeedifard, Georgia Institute of Technology
- "Grid-Forming Photovoltaic Inverter: Opportunities and Challenges," Dr. Hariharan Krishnaswami, U.S. Department of Energy
- "The Advanced Grid Innovation Lab for Energy: A Collaborative Program of the New York Power Authority (NYPA)," Dr. George Stefopoulos, NYPA
- "Microgrid Testbeds at Different Scales for Research and Education," Prof. Beibei Ren, Texas Tech University
- "Resilient Architectures and Algorithms for Generation Control of Inertialess ac Microgrids," Prof. Alejandro Dominguez-Garcia, University of Illinois at Urbana-Champaign
- "Nonlinear Decentralized Control for Future Grids," by Prof. Brian Johnson, University of Washington
- "Multi-Scale Control of Power Electronics for Power Systems," Prof. Sudip K Mazumder, University of Illinois at Chicago
- "High-Frequency Power Electronics at the Grid Edge: Opportunities and Challenges," Prof. Minjie Chen, Princeton University
- "Impedance-Based Evaluation of Stability Impacts of Inverter-Based Resources," Dr. Shahil Shah, National Renewable Energy Laboratory.

The workshop was a success, and the participants found it informative and useful for further work. It will be organized annually in the future.

FIG 1 Workshop attendees gather for the first day.

About the Author

Qing-Chang Zhong (zhongqc@ieee.org) received his Ph.D. degree in control theory and engineering from Shanghai Jiao Tong University, China, in 2000 and his Ph.D. degree in control and power engineering from Imperial College London in 2004. He is the Max McGraw Endowed Chair Professor in energy and power engineering in the Department of Electrical and Computer Engineering, Illinois Institute of Technology, Chicago, and founder and chief executive director of Syndem, Chicago. His research focuses on power electronics, advanced control theory, and the seamless integration of both to address fundamental challenges in energy and power systems. He is a Fellow of the IEEE.

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12 IEEE POWER ELECTRONICS MAGAZINE March 2020

Figure 5 Dissemination article published in IEEE Power Electronics Magazine, March 2020

9 Future Activities

9.1 Keynote talk at IECON 2020

The PI is invited to give a keynote talk on Power-Electronics-Enabled Autonomous Power Systems: Next-Generation Smart Grids at IECON 2020, which is the 46th Annual Conference of the IEEE Industrial Electronics Society (IES), to be held in Singapore during October 18-21, 2020. More details of the talk can be found at https://www.iecon2020.org/Keynote2.html.

9.2 Special Session at IECON2020

The Organizing Committee members Ziang Zhang, Sairaj Dhople, and Brain Johnson are organizing a special session entitled "Grid-forming Inverters in Future Power Systems" at the 46th Annual Conference of the IEEE Industrial Electronics Society (IECON), to be held in Singapore during October 18-21, 2020. More details of the session can be found at https://www.iecon2020.org/ApprovedSpecialSessions1.html. The special session aims to stimulate discussions and facilitate communications among the communities of control systems theory, power electronics, and power systems to ensure the at-scale and seamless integration of grid-forming inverters in future power networks. Five manuscripts have been accepted by the conference.

10 Sample Feedbacks and Comments

- "I definitely got some ideas, established some networking links, and potential funding venues. In addition, based on the workshop presentations and discussions, I have already discussed some preliminary ideas with some of the attendees (that I met during the workshop) and plan to pursue collaborative research project(s)."
- "Travel support is essential and instrumental for many faculty members from a number of institutions. Without it, it could be challenging (while I very much desire to attend and provoke some thoughts)."
- "This was a great workshop bringing together the leading experts in the area for enlightening talks. We are looking forward to future collaboration particularly on integrating microgrid into undergraduate research and education. I am thinking to design a new course on microgrid modeling and control for undergraduates at BBB University. This workshop definitely exposed me some new ideas on how to revamp the power systems and electronics curricula. Will ask you more on this in the future."
- "It will be wonderful if this workshop can be made into an annual event!"
- "Also, thank you very much for your effort to organize the amazing workshop! It was a great experience to meet all the people in the area and to look around IIT and the labs."
- "I really enjoyed participating in the workshop; it was very well organized and the line-up was outstanding."
- "It was indeed a successful workshop and I have learned a great deal! Thank you for your leadership."
- "It is very informative, intensive and helpful. I enjoy it very much and I really wish we could have more high quality workshops like this in the future."
- "An excellent workshop on a timely topic."
- "The workshop was very well-organized and the talks covered different aspects of power electronics-enabled power systems. The demo/tour of the Syndem lab and the IIT microgrid were quite impressive! I enjoyed my visit at the workshop and interactions with many friends and colleagues."

- "I would be interested in attending your annual events."
- "... a wonderful workshop of which the topic is very interesting. I enjoyed it very much."
- "... a very successful and exciting workshop. It was very informative for me and I am sure that many other junior faculty have the same feeling."
- "enlightening," "informative," "powerful," "forward-looking," "great," "excellent," "amazing," "futuristic," "insightful."

Appendices

A. List of Registered Participants

In total, 134 participants registered for the workshop and they are listed below in the alphabetical order of their first names.

Abraham Ellis	Office of Electricity, DOE
Adel Nasiri	UW-Milwaukee
Ahmad Khan	Kansas State University
Alejandro Dominguez-Garcia	University of Illinois
Alex Flueck	Illinois Institute of Technology
Alex Huang	University of Texas at Austin
Ali Davoudi	University of Texas at Arlington
Ali Emadi	McMaster University
Alireza Khaligh	University of Maryland & NSF
Amir Sajadi	Public Service Commission of Wisconsin
Anil Pahwa	National Science Foundation
Ankit Singhal	Pacific Northwest National Laboratory
Ankita Desai	Illinois Institute of Technology
Arash Khoshkbar-Sadigh	Pennsylvania State University
Arijit Banerjee	University of Illinois at Urbana-Champaign
Aritra Kundu	Illinois Institute of Technology
Ayman EL-Refaie	Marquette University
Beibei (Helen) Ren	Texas Tech University
Bharat Balagopal	North Carolina State University
Bhuvaneswari Ramachandran	University of West Florida
Bikiran Guha	Illinois Institute of Technology
Bishnu Bhattarai	Pacific Northwest National Laboratory
Bo Chen	Argonne National Laboratory
Bob Lasseter	University of Wisconsin
Boqi Xie	Argonne National Laboratory
Brian Johnson	University of Washington
Bryan Lieblick	Plexim

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Carrie Hall	Illinois Institute of Technology
Charalambos Konstantinou	Florida State University
Charles Murray	Switched Source
Chee-Wooi Ten	Michigan Technological University
Cui Wang	Nanchang Institute of Technology
Deepak Divan	Georgia Institute of Technology
Dimitrios Thiakos	S&L
Dong Cao	University of Dayton
Dongbo Zhao	Argonne National Laboratory
Duo Wang	Illinois Institute of Technology
Faraj Alyami	Western Michigan University
Fred Wang	University of Tennessee, Knoxville
George Gross	University of Illinois at Urbana-Champaign
George Stefopoulos	New York Power Authority
Greg Salas	Group NIRE
Guorui Zhang	Southwest Jiaotong University
Hamed Nademi	Rensselaer Polytechnic Institute
Hamid Arastoopour	Illinois Institute of Technology
Hanif Livani	University of Nevada Reno
Hao Xu	University of Nevada Reno
Hariharan Krishnaswami	ManTech, Contractor DOE Solar Office
Hengzhao Yang	New Mexico Institute of Mining and Technology
Herbert L Hess	University of Idaho
Hong Fan	Shanghai University of Electric Power
Hong Wang	Oak Ridge National Laboratory
Hussein Alameri	Western Michigan University
Ian Brown	Illinois Institute of Technology
Irfan Khan	Texas A&M University
Jafar Saniie	Illinois Institute of Technology
Jairo Cervantes	University of Nebraska-Lincoln
Jason Poon	Stanford University
Jiangbiao He	University of Kentucky
Jin Ye	University of Georgia
Jing Wang	Bradley University
John Seuss	S&C Electric Co
John Shen	Illinois Institute of Technology
Jungwon Choi	University of Minnesota
Junhui Zhao	University of New Haven
Junjian Qi	University of Central Florida
Kai Sun	University of Tennessee, Knoxville
Komal S Shetye	Texas A&M University

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Liang Du	Temple University
Lina He	University of Illinois at Chicago
Maggie Cheng	Illinois Institute of Technology
Mahesh Krishnamurthy	Illinois Institute of Technology
Mani Venkatasubramanian	Washington State University
Manohar Chamana	Texas Tech University
Marcelo Godoy Simoes	Colorado School of Mines
Maryam Saeedifard	Georgia Institute of Technology
Masood Parvania	University of Utah
MASOUD BARATI	University of Pittsburgh
Masoud Karimi	Mississippi State University
Matthew Bossart	University of Colorado
Mengqi (Maggie) Wang	University of Michigan-Dearborn
Michael L. McIntyre	University of Louisville
Minjie Chen	Princeton University
Mohammad Khodayar	Southern Methodist University
Mohammad Shadmand	Kansas State University
Mohammad Shahidehpour	Illinois Institute of Technology
Mohsen Hosseinzadehtaher	Kansas State University
Muhittin Yilmaz	Texas A&M University-Kingsville
Ned Mohan	University of Minnesota
Payman Dehghanian	George Washington University
Peng Zhang	Stony Brook University
Prosper Panumpabi	University of Illinois at Urbana-Champaign
Qifeng Li	University of Central Florida
Qing-Chang Zhong	Illinois Institute of Technology
Radha Sree Krishna Moorthy	Oak Ridge National Laboratory
Rajat Kamble	Illinois Institute of Technology
Reinaldo Tonkoski	South Dakota State University
Rick Wallace Kenyon	University of Colorado
Robert Wills	Intergrid
Sadik Kucuksari	University of Northern Iowa
Sairaj Dhople	University of Minnesota
Sandeep Nimmagadda	Texas Tech University
Sara Ahmed	University of Texas at San Antonio
Shahil Shah	NREL
Shijia Zhao	Argonne National Laboratory
Shrirang Abhyankar	Pacific Northwest National Laboratory
SHUO WANG	University of Florida
Sina Vahid	Marquette University
Sitoshna Jatty	Illinois Institute of Technology

Sonny Xue	ORNL
Stephen Williams	S&C Electric
Sudip K Mazumder	University of Illinois at Chicago
Thanh Long Vu	Pacific Northwest National Laboratory
Vahid Dargahi	University of Washington, Tacoma
Vikram Bhattacharjee	Hyliion,Inc.
Weiping Shi	Texas A&M University
Wen Huang	Hunan University
Wencong Su	University of Michigan-Dearborn
Xiaonan Lu	Temple University
Xin Liu	Illinois Institute of Technology
Yan Li	Pennsylvania State University
Yibo Zhang	Illinois Institute of Technology
Yichen Zhang	Argonne National Laboratory
Yoav Sharon	S&C Electric Co.
Yue Cao	Oregon State University
Yuting Tian	Argonne National Laboratory
Zhangxin Zhou	Texas A&M University
Zhenyu (Henry) Huang	Pacific Northwest National Laboratory
Zhi Zhou	Argonne National Laboratory
Zhixi Deng	Illinois Institute of Technology
Zhixin Miao	University of South Florida
Ziang (John) Zhang	Binghamton University
Zijun Lv	Illinois Institute of Technology
Zuyi Li	Illinois Institute of Technology

B. Slides

The slides of the presentations are available online at the workshop website http://peac.ece.iit.edu/events/nsf-workshop-on-power-electronics-enabled-operation-of-power-systems/.