Introduction to the Issue on Signal Processing in Smart Electric Power Grid

THIS special issue is intended as a forum for advancing and applying signal processing techniques to facilitate the development of *smart* electric power grid, commonly known as *smart grid*. The issue starts with a survey paper followed by twelve regular papers. The survey paper provides an overview of the problem of state estimation and energy management in smart grid, with an emphasis on employing distributed estimation techniques for distributed state estimation, economic dispatch and optimal power flow. The twelve regular papers that follow address various topics relevant to signal processing for smart grid.

Electric power grid is one of the most complex man-made infrastructures. Over the years, due to the ever-increasing demand for electric power, the grid is stressed, running up against its limitations on capacity and complexity, which leads to more occurrences of brown-outs and black-outs. The current power grid is not efficient, not completely reliable, and it is also vulnerable to malicious attacks. This situation is exacerbated by the concerns for global climate change and national security as it relates to the power grid. In particular, the need of integrating an increasing level of renewable and intermittent power generations such as wind and solar sources requires the system operation be able to handle non-dispatchable stochastic generation and guarantee grid-wide robustness and efficiency.

Given the current situation of the power grid, there has been a great deal of interest in *smart grid* technology. Simply stated, the smart grid technology is an integration of information and communication technologies with power grid technologies related to the generation, transmission, distribution, and consumption of electricity. It is aimed to make the power grid more efficient, dependable, and secure. At the same time, the smart grid vision calls for consumer empowerment and self-healing capability that necessitate distributed sensing and metering, and a reliable bidirectional digital communication infrastructure. Furthermore, the consumers may also become producers of renewable energy with the capability of controlling the energy consumption, production, exchange and storage locally. Facilitated by proper applications of information and communication technologies, smart grid can transform our lives similarly to the way that internet has transformed our lives.

Over the years, research in signal processing has played an important role in the advent and continued evolution of internet, telecommunication and wireless communication technologies. Conventional signal processing research is quite adept at extracting timely and relevant information from noise-contaminated, or even distorted, signals through filtering, estimation, and detection to facilitate decision-making and control actions. This is further empowered by statistical methods, machine learning algorithms, optimization techniques and efficient numerical algorithms. An important question now for researchers in the signal processing community is "what role can signal processing research play in the development of smart grid technology."

Glancing through Title XIII, Sec. 1301, Statement of Policy on Modernization of Electricity Grid (a policy statement issued by the U.S. Department of Energy in 2008), researchers can see many opportunities in applying, among others, distributed signal processing, machine learning, optimization, statistical signal detection and estimation, to enable many of the envisioned characteristics of the smart grid. Those characteristics include increased use of digital information and control technology to improve the grid's reliability, security and efficiency, dynamic optimization of grid operations (e.g., power dispatch), demand response, incorporation of demand-side resources and integration of energy-efficient and environmentally friendly resources, distribution automation, and integration of smart appliances and consumer devices. Signal processing offers the tools needed to convert measurement data to information and transform information into actionable intelligence by providing timely and reliable information throughout the smart grid. In essence, signal processing techniques will provide vital tools to enable timely and reliable sensing, communication, computing and control for the persistently dependable operations of the smart grid. The result will be a grid with improved situation awareness, faster and more accurate control actions to detect and isolate faults, improved assurance of power quality, higher levels of energy efficiency and integrated consumer responsiveness. The smart grid research also provides a rich cross-disciplinary playground that can facilitate broadening the scope of signal processing research. For example, concepts from economic principles such as game theory are useful to model and resolve complex interactions among the consumers, minigrids and utility companies.

The twelve papers included in this special issue address various signal processing research topics as they relate to the smart grid. The topics addressed by these papers include using signal processing techniques for state estimation, electric vehicle charging as it relates to intermittent renewable energy and power flow management, fault detection, electricity market forecasting with machine learning methods like kernel-based learning, demand-side management, energy consumption models, and power balancing. This special issue thus provides strong evidence that statistical signal processing, machine learning, and various optimization methods are all fertile grounds for signal processing researchers to explore as they venture into the smart grid technology.

The guest editors would like to take this opportunity to express their sincere appreciation to many reviewers, whose com-

Digital Object Identifier 10.1109/JSTSP.2014.2361537

ments have helped improve the quality of the accepted articles. We are confident that readers will find this collection of articles interesting and useful.

YIH-FANG HUANG, *Lead Guest Editor*
University of Notre Dame
Notre Dame, IN 46556 USA

SHALINEE KISHORE, *Guest Editor*
Lehigh University
Bethlehem, PA 18015 USA

VISA KOIVUNEN, *Guest Editor*
Aalto University
Aalto FIN00076, Finland

DANILO MANDIC, *Guest Editor*
Imperial College London
London SW7 2BT, U.K.

LANG TONG, *Guest Editor*
Cornell University
Ithaca, NY 14853 USA

Yih-Fang Huang (F'95) is Professor of Electrical Engineering and Senior Associate Dean for Education and Undergraduate Programs in the College of Engineering. He received his B.S.E.E. degree from National Taiwan University, the M.S.E.E. degree from University of Notre Dame, and the M.A. and Ph.D. from Princeton University. He served as chair of Notre Dame's Electrical Engineering department from 1998 to 2006. His research work employs principles in mathematical statistics to solve signal detection and estimation problems that arise in various applications that include wireless communications, distributed sensor networks and, more recently, smart electric power grid.

He received the Golden Jubilee Medal of the IEEE Circuits and Systems Society in 1999, served as Vice President in 1997–98 and was a Distinguished Lecturer for the same society in 2000–2001. At the University of Notre Dame, he received Presidential Award in 2003, the Electrical Engineering department's Outstanding Teacher Award in 1994 and in 2011, the Rev. Edmund P. Joyce, CSC Award for Excellence in Undergraduate Teaching in 2011, and the Engineering College's Outstanding Teacher of the Year Award in 2013.

In Spring 1993, Dr. Huang received the Toshiba Fellowship and was Toshiba Visiting Professor at Waseda University, Tokyo, Japan. From April to July 2007, he was a visiting professor at the Munich University of Technology, Germany. In Fall, 2007, he was awarded the Fulbright-Nokia scholarship for lectures/research at Helsinki University of Technology in Finland.

Shalinee Kishore (M'03) is an Associate Professor in the Department of Electrical and Computer Engineering at Lehigh University, Bethlehem, PA, USA. She obtained the Ph.D. and M.A. degrees in electrical engineering from Princeton University, Princeton, NJ, USA, and the M.S. and B.S. degrees in electrical engineering from Rutgers University, New Brunswick, NJ, USA. From 1998 to 2001, she was a visiting researcher at AT&T Labs-Research and she was a Visiting Fellow at Princeton University from 2013–2014. Prof. Kishore is the recipient of the Presidential Early Career Award for Scientists and Engineers (PECASE), the National Science Foundation CAREER Award, and the AT&T Labs Fellowship Award. She has also served as a Kavli Fellow for the National Academy of the Sciences.

Her research interests are in communications theory, networks, and signal processing, with application in wireless systems and smart electricity systems. In the area of smart grids, she is developing models and algorithms for demand response, load shaping, real-time flow measurements, renewable energy integration, and electricity market interactions.

Visa Koivunen (F'11) received his D.Sc. (EE) degree with honors from the University of Oulu, Department of Electrical Engineering. He received the primus doctor (best graduate) award among the doctoral graduates from 1989 to 1994. He is a member of Eta Kappa Nu. From 1992 to 1995 he was a visiting researcher at the University of Pennsylvania, Philadelphia, USA. From 1997 to 1999 he was faculty at Tampere University of Technology, Finland. Since 1999 he has been a full Professor of Signal Processing at Aalto University (formerly known as Helsinki University of Technology), Finland. He holds the Academy professor position (distinguished professor nominated by the Academy of Finland). He was a Principal Investigator in the SMARAD Center of Excellence in Research nominated by the Academy of Finland in 2002–2013. From 2003 to 2006 he was also adjunct full professor at the University of Pennsylvania, Philadelphia, USA. During his sabbatical term year 2007 he was a Visiting Fellow at Princeton University, NJ, USA. He has also been a part-time Visiting Fellow at Nokia Research Center (2006–2012). He has made multiple extended research visits to Princeton University. He spent a sabbatical term at Princeton University for the academic year 2013–2014.

Dr. Koivunen's research interests include statistical, communications, sensor array and multichannel signal processing. He has published about 350 papers in international scientific conferences and journals. He holds 6 US patents. He co-authored the papers receiving the best paper award in IEEE PIMRC 2005, EUSIPCO'2006, EUCAP (European Conference on Antennas and Propagation) 2006 and COCORA 2012. He was awarded the IEEE Signal Processing Society best paper award for the year 2007 (with J. Eriksson). He served as an associate editor for IEEE SIGNAL PROCESSING LETTERS, IEEE TRANSACTIONS ON SIGNAL PROCESSING, *Signal Processing* and *Journal of Wireless Communication and Networking*. He is a member of the guest editor team for the IEEE JSTSP special issue on Smart Grids. He is a member of editorial board for IEEE SIGNAL PROCESSING MAGAZINE. He has been a member of the IEEE Signal Processing Society technical committees SPCOM-TC and SAM-TC. He has also served in the IEEE SPS Industrial Relations committee. He was the general chair of the IEEE SPAWC conference 2007 conference in Helsinki, Finland June 2007. He is the Technical Program Chair for the IEEE SPAWC 2015 as well as Array Processing track chair for 2014 Asilomar conference. Dr. Koivunen is a Fellow of the IEEE.

Danilo Mandic (F'13) obtained his Ph.D. degree in the area of nonlinear adaptive systems from Imperial College London, UK, where he is currently a Professor of Signal Processing. He has been working in the areas of nonlinear and multidimensional adaptive filters, time-frequency analysis and complexity science. His research has found applications in biomedical engineering, and renewable energy and smart grid. He has published two research monographs: *Recurrent Neural Networks for Prediction* (Wiley 2001) and *Complex Valued Nonlinear Adaptive Filters: Noncircularity, Widely Linear and Neural Models* (Wiley 2009). Dr. Mandic has held visiting positions in RIKEN (Japan) and KU Leuven (Belgium). He has been an Associate Editor for IEEE TRANSACTIONS ON NEURAL NETWORKS and *Learning Systems*, IEEE SIGNAL PROCESSING MAGAZINE, and IEEE TRANSACTIONS ON SIGNAL PROCESSING. He is also a Member of the Task Force on Smart Grid within the IEEE Computational Intelligence society and has extensively worked on power quality estimation in unbalanced power systems. Dr. Mandic has received President's award for excellence in postgraduate supervision at Imperial College London.

Lang Tong (F'05) is the Irwin and Joan Jacobs Professor in Engineering at Cornell University, Ithaca, New York. He received his M.S.E.E. degree and Ph.D. degree from the University of Notre Dame. He received the 2004 Best Paper Award from the IEEE Signal Processing Society, the 2004 Leonard G. Abraham Prize Paper Award from the IEEE Communications Society, and the 1993 Outstanding Young Author Award from the IEEE Circuits and Systems Society. He is a coauthor of seven student paper awards including two IEEE Signal Processing Society Young Author Best Paper Awards (in 2000 and 2008) for papers published in the IEEE TRANSACTIONS ON SIGNAL PROCESSING. He was named as a 2009 Distinguished Lecturer by the IEEE Signal Processing Society. He was the recipient of the 1996 Young Investigator Award from the Office of Naval Research. His research interests include statistical inference, decisions and, signal processing; future power energy systems and smart grids; information security; wireless communications and information theory. Dr. Lang Tong is a Fellow of IEEE.