Energy Internet

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I. BACKGROUND

As one of the most important infrastructures, the energy system covers electricity, heating, cooling, natural gas, oil, coal, hydrogen, etc. Energy security, energy equity, and environmental sustainability are the well-known energy trilemma. The energy system is the largest source of carbon emissions; therefore, the goal for carbon neutrality puts forward very high requirements. Renewable energy will account for the majority of generation in the future, while the current energy system is not ready.

This special section provides an overview of the concept, architecture, key technologies, and potential applications of energy internet.

A. Current Energy System

Currently, most energy systems are designed, built, and operated separately, which sets many barriers to their coordination to exploit synergies. For example, renewable energy curtailment is a serious problem in areas where renewable energy penetration is high. However, the curtailed renewable energy can be transformed into hydrogen or heat, thereafter utilized in a highly efficient way. In addition, most users are passive consumers, and energy is transmitted unidirectionally from the generation to the demand. The flexibility in the demand side is not well exploited. Smart grid is a major advancement in the last decade that can change to a large extent the electric power system by exploiting distributed generators, renewable energy, demand response, and other technologies. However, it is still mainly focusing inside the electricity system and does not take full advantage of the synergy of the whole energy system.

B. Emerging Paradigm: Low-Carbon Energy Ecosystem

Many countries have set goals for carbon neutrality. Renewable energy development and energy efficiency are two key solutions for carbon neutrality, which will reshape the energy system. In International Energy Agency's (IEA's) pathway to net zero, almost 90% of global electricity generation in 2050 comes from renewable sources, with solar photovoltaic (PV) and wind together accounting for nearly 70%. However, challenges are emerging in the energy transition. One challenge is the security, including the energy supply security and energy operating security due to the high uncertainty and intermittency of renewable energy generation, cyber-attacks, extreme events such as earthquakes, typhoons, very hot and cold weather, etc. Another challenge is the cost. The cost of energy transition should be acceptable, thus the transition is sustainable. Therefore, the intriguing question brought to the attention of the energy community is: how to build a low-carbon energy ecosystem which is also secure and affordable?

C. Road to Next-Generation Energy System

Energy internet (EI), a deep combination of the energy system and the internet, is an emerging topic for the next-generation energy system. EI can support the new energy ecosystem with better interconnection, openness, and flexibility. The vision of EI is to build a low-carbon energy ecosystem, which is secure, efficient, open, and shared. It aims to accommodate high penetration of renewable energy, improve energy efficiency, and create a novel sharing economy to reduce the cost of energy supply. The mission of EI is to break all kinds of barriers in that ecosystem, so that more interconnectivity and sharing can be achieved among energy systems, creating a fertile ground for massive entrepreneurship and innovations in the energy sector.

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D. Energy Internet: The Enabling Technology

EI is distinguished from the concept of "smart grid" in the following ways.

1) Internet thinking will reshape the energy networks. EI will be constructed based on synergy of multienergy systems, including heating, cooling, gas, hydrogen, transportation, and electricity. For EI, it is essential to remove the existing barriers among different energy carriers and produce new flexibilities and achieve high efficiency by interconnecting these heterogeneous energy subsystems. Energy routers, energy hubs, multienergy storages, and plug-and-play techniques could be utilized to build an internet-like energy grid, which could support more versatile interconnections between supply and demand.
2) New internet and IT techniques, such as new-generation communication technologies, ubiquitous decentralized control methods, and new computing architectures coordinating between the cloud and the edge device, will empower the energy network with more smartness and more openness.
3) New energy policies and energy markets based on sharing economy should be designed considering widespread energy P2P trading. EI should be realized to enable complex interaction among multiparticipants with not only energy transactions but also diverse services.

E. State of the Art

As an emerging concept, which is still evolving and developing, EI has drawn recently more and more attention by both academia and industry. As a cross-disciplinary research topic, it is of common interest from different research groups in different areas. An annual IEEE Conference on Energy Internet and Energy Systems Integration (IEEE EI^2) was launched in 2017 and has been successfully held five times, each of which attracted 1000+ attendees and 1000+ submissions. IEEE Power and Energy Society (PES) has set up a new Energy Internet Coordinating Committee in 2020. The State Grid Corporation of China, the largest power company in the world, has announced a new vision to become a leading EI enterprise. In Europe, integrated energy system/multienergy systems is a topic of great interest, on which many projects have been carried out in recent years. In the United States, National Science Fundation (NSF) sponsored the FREEDM Research Center, Raleigh, NC, USA, which addresses EI, among other topics. The research activities conducted to date, encompass different fundamental research issues and several applications, including modeling, simulation, and design of EI; fundamental analysis theory and methods for EI; emerging key facilities of EI, such as energy router, energy hub, energy storage, electrical vehicles, wireless energy transfer, and dc networks; plug-and-play technologies; enabling techniques of information and communication for EI, such as cloud computing, big data, the Internet of Things (IoT), blockchain, and artificial intelligence (AI) techniques; and cyber-physical systems for EI, business models, market, and corresponding energy policies for EI.

F. Fundamental Gap of Knowledge in Research

Despite the fact that the number of academic articles related to EI has significantly increased in the last ten years, especially accelerated after 2015, there still remain many major challenges for EI. The heterogeneous energy system follows different physical rules for different disciplines, thus the modeling, simulation, control, operation, and planning of the integrated energy system (IES) lack unified and efficient methods, especially when dealing with the detailed dynamics of large-scale energy systems. Moreover, the application of advanced IT technologies in EI is just getting started. The generic architecture and analysis methods across cyber and physical (energy) space require new insights. Furthermore, multiple participants in a sharing-economy-based market have concerns in data security and privacy preservation. These topics are still not well covered and need attention for further development among scientists who work across multiple disciplines, including power and energy, power electronics, information and communication theories, physics, metamaterials, computer science, data science, and machine learning, engineering, economics, environmental science, psychology, and sociology.

G. Importance of the Topic to the Readers of the Proceedings of the IEEE

The objective of the present special section is to deliver a whole picture and much more profound discussions on the concept, architecture, key technologies, and potential applications of EI. The special section is designed to fill the mentioned fundamental gap of knowledge among researchers working on EI across several different disciplines, including the areas of power and energy, power electronics, information theory and technology, optimization, communication theory, the IoT, and data science. We believe that the special section will raise research interests and inspire novel ideas in the related areas, which will definitely advance the next-generation energy system, and benefit students, practitioners, and researchers from both industry and academia. More activities and information can be found within the IEEE PES Energy Internet Coordinating Committee (EICC) (https://cmte.ieee.org/pes-eicc/).

II. OVERVIEW OF THE SPECIAL SECTION

The special section collects four papers that provide comprehensive perspectives on EI, including the fundamental analysis theory and method, the modeling and framework, the emerging key facilities, the enabling techniques for information and communication, etc. These papers cover the physical level, the cyber level, and the business level, which form the architecture of the EI.

The four articles are briefly introduced here.

Energy-Circuit-Based Integrated Energy Management System: Theory, Implementation, and Application

by B. Chen, Q. Guo, G. Yin, B. Wang, Z. Pan, Y. Chen, W. Wu, and H. Sun

This article presents a novel energy circuit method for IESs modeling and analysis. The energy circuit method unifies the analyses of the heterogeneous integrated energy networks in the same mathematical form, in which the original partial differential equation (PDE) models are transformed into algebraic equations in frequency domain. The method can highly improve the computation performance of the large-scale IES, which is the physical foundation of EI. Based on this method, an integrated energy management system (IEMS) is implemented and applied in many real-world engineering demonstrations.

Plug-and-Play Algorithms for the Efficient Coordination of Active Distribution Grids

by I. Kouveliotis-Lysikatos, D. I. Koukoula, A. L. Dimeas, and N. D. Hatziargyriou

This article discusses the decentralized and distributed coordination architectures for the operation of active distribution grids aiming at effectively coping with their complexity. Under the multiagent system (MAS) framework, plug-and-play decision-making models based on distributed optimization algorithms are presented for different operational aspects of active distribution grids. These methods can support the flexibility and self-adaptability of the EI.

On an Information and Control Architecture for Future Electric Energy Systems

by L. Xie, T. Huang, P. R. Kumar, A. A. Thatte, and S. K. Mitter

This article presents an information and control architecture for future electric energy systems to meet the goals of decarbonization and electrification. It provides a historical review of the architecture of networked systems, and outlines a possible cyber-physical architecture for EI of the future, by identifying several new information and control loops along with their spatial and temporal scales of operation.

Application of Distributed Ledger Technology in Distribution Networks

by Y. Zhou, A. N. Manea, W. Hua, J. Wu, W. Zhou, J. Yu, and S. Rahman

This article presents a comprehensive review of the distributed ledger technology (DLT) applied in distribution networks. The mapping of the DLT features and distribution system operator (DSO) needs are discussed, and the detailed DSO functions are identified with the potential application of DLT. The development of seven key DSO functions with high DLT potential are analyzed and discussed from the technical, legal, and social perspectives, which are important for building a trustworthy, secure, and reliable business model of EI.

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ABOUT THE GUEST EDITORS

Hongbin Sun (Fellow, IEEE) received the double B.S. degrees from Tsinghua University, Beijing, China, in 1992, and the Ph.D. degree from the Department of Electrical Engineering, Tsinghua University, in 1997.

He is currently a Changjiang Scholar Chair Professor of China and a tenured Full Professor of electrical engineering and the Director of the Energy Management and Control Research Center, Tsinghua University. He is also the Executive President of the Taiyuan University of Technology, Taiyuan, China. From 2007 to 2008, he was a Visiting Professor with the School of Electrical Engineering and Computer Science, Washington State University, Pullman, Washington, USA. In the past 20 years, he led a research group at Tsinghua University to develop a commercial system-wide automatic voltage control system, which has been applied to more than 100 electrical power control centers in China as well as the control center of Pennsylvania-New Jersey-Maryland (PJM) interconnection, the largest regional power grid in USA. He has authored/coauthored more than 600 peer-reviewed articles. His research interests include energy management systems, automatic voltage control, energy internet, and energy system integration.

Dr. Sun is the Chair of the IEEE Power and Energy Society (PES) Energy Internet Coordinating Committee and the Vice Chair of the Committee of Energy, World Federation of Engineering Organizations (WFEO). He was the Founding Chair of the IEEE Conference on Energy Internet and Energy System Integration in November 2017. He won the second prize of the China National Technology Innovation Award in 2008 and the first prize in 2018, the National Distinguished Teacher Award in China in 2009, and the National Science Fund for Distinguished Young Scholars of China in 2010.

Nikos D. Hatziargyriou (Life Fellow, IEEE) is a Professor in power systems at the National Technical University of Athens, Athens, Greece. He was the Chair of the EU Technology and Innovation Platform on Smart Networks for Energy Transition (ETIP-SNET) representing European Distribution System Operators (E.DSO). Currently, he is a Senior Consultant. He has participated in more than 60 research and development projects funded by the EU Commission, electric utilities, and manufacturers for both fundamental research and practical applications. He is included in the 2016, 2017, and 2019 Thomson Reuters lists of the top 1% most cited researchers and is 2020 Globe Energy Prize Laureate. He is the author of the book *Microgrids: Architectures and Control* and of more than 300 journal publications and 600 conference proceedings papers.

Dr. Hatziargyriou has over ten-year industrial experience as the Chairperson and the CEO of the Hellenic Distribution Network Operator and as the Executive Vice-Chair of the Public Power Corporation. He is an Honorary Member of Conseil International des Grands Réseaux Electriques (CIGRE) and the past Chair of CIGRE SC C6 "Distribution Systems and Distributed Generation." He has received the IEEE Power and Energy Society (PES) Prabha S. Kundur Power System Dynamics and Control Award. He was the past Chair of the Power System Dynamic Performance Committee (PSDPC) and the past Editor-in-Chief of IEEE TRANSACTIONS ON POWER SYSTEMS and currently PES Editor-in-Chief At Large.