Guest Editorial
Introduction to Special Issue on "Cloud-Edge-End Orchestrated Computing for Smart Grid"

THE integration of distributed energy resources (DER) into the smart grid through digitalization has transformed the power grid into a more decentralized system, enhancing energy efficiency and resilience during significant catastrophes. However, the integration of a large number of DERs into the transmission and distribution networks poses reliability challenges due to the intermittent nature of renewable energy sources. To tackle this, smart grids have been using advanced metering infrastructure (AMI) and Internet of Things (IoT) devices for over two decades to improve grid observability and enable near-real-time forecasting of continent-wide anomalies. Cloud-edge-end orchestrated computing can achieve hierarchical management and innovative operational strategies, such as multi-level control and optimization of all-grid-level DERs, voltage and frequency regulation using phasor measurement units (PMU), and special protection schemes (SPS) to detect and prevent potential faults or large-scale cyber-attacks.

This special issue has been curated to showcase ground-breaking research and engineering practices on cloud-edge-end orchestrated computing for proactive distribution/transmission systems in smart grids, featuring new theories, applications, and case studies. A total of 35 submissions were received, and following a rigorous evaluation by experts in the field, 12 papers were selected for publication in this issue.

The first paper, "*Carbon-Aware Load Balance Control of Big Data Centers With Renewable Generations*" by W. Lin et al. focuses on reducing carbon emissions in data centers using renewable energy sources while accounting for uncertainties in electricity prices, fuel mix, and renewable generation. The authors propose a load balance control framework that facilitates online job scheduling strategies for data centers, enabling precise matching of workload and renewable energy power generation. Simulations using real-world data from multiple states in Australia demonstrate the effectiveness of the proposed framework in reducing costs and carbon emissions in the presence of uncertainties.

The second paper, authored by H. Zhou et al. and titled "*Joint Optimization of Computing Offloading and Service Caching in Edge Computing-based Smart Grid*", addresses the joint optimization of computing offloading and service caching in an edge computing-based smart grid. The authors formulate the problem as a mixed-integer non-linear program (MINLP) with the goal of minimizing the task cost of the system. The original problem is divided into a master problem and sub-problem, and a collaborative computing offloading and resource allocation method (CCORAM) is proposed to solve the optimization problem. CCORAM comprises two low-complexity algorithms: a gradient descent allocation algorithm that determines the computing resource allocation strategy and a game theory-based algorithm that determines the computing strategy. Simulation results demonstrate that CCORAM, which has low time complexity, is very close to the optimal method and outperforms other benchmark methods.

The third paper in this collection, titled "*Transactive Operational Framework for Internet Data Centers in Geo-Distributed Local Energy Markets*" and authored by C. Guo et al. presents a two-stage transactive operation model for a group of geo-distributed internet data centers (IDCs) participating in local energy markets. In the first stage, an ex-ante bidding model is proposed to optimize the scheduling of the IDCs' cyber-energy resources, computing requests, and on-site battery energy storage system while determining energy trading prices in local energy markets to minimize the total cost. To solve the mixed-integer non-linear optimization problem in the first stage, the authors utilize an effective evolutionary computation algorithm. In the second stage, a real-time energy balancing model is introduced to adjust the energy volume of each IDC to offer energy balancing services with the maximum profit, thus reducing the supply-demand energy imbalance in the located energy market. The framework models the coupling relationship between the IDCs' operation strategies, energy trading prices, and market deviation signals. The proposed framework's effectiveness is demonstrated through extensive numerical case studies.

The fourth paper, authored by X. Yang et al. and titled "*Cloud-Edge-End Intelligence for Fault-tolerant Renewable Energy Accommodation in Smart Grid*", presents a novel cloud-edge-end orchestrated computing scheme for efficiently repairing missing values and obtaining optimal policies in two separate layers. In the first layer, deep learning-based algorithms are deployed to perceive the characteristics and repair the missing values. In the second layer, deep reinforcement learning-based algorithms are utilized to obtain optimal policies. The efficacy of the proposed fault-tolerant renewable energy accommodation algorithm is demonstrated through simulations on a real power grid dataset.

The fifth paper in this collection, authored by C. Chen et al. and titled "*An End-Cloud Collaborated Framework for Trans-*

Digital Object Identifier 10.1109/TCC.2023.3271489

ferable Non-Intrusive Load Monitoring", proposes an end-cloud collaborated framework for transferable non-intrusive load monitoring (NILM). The work begins by designing an end-to-end model with a multi-scale convolutional architecture for identifying the activation of a specified target appliance using current waveforms. This model can be independently deployed as needed. Additionally, a transfer learning framework for NILM is established. The model is first pre-trained on the cloud and then continuously fine-tuned on the terminal side using a pseudo-supervised method, where the group-weighted cross entropy (GWCE) is defined as the loss function. Based on experimental results from two public datasets, the proposed model structure exhibits outstanding generalization ability across different appliances and scenarios. The transfer learning procedure with GWCE enhances the identification ability of the pre-trained model, particularly for unfamiliar scenarios. This work has practical applications with great potential, especially when equipped with an NILM device capable of terminal-side intelligence.

The sixth paper in this collection, written by K. Fan et al. and titled "*MSIAP: A Dynamic Searchable Encryption for Privacy-Protection on Smart Grid with Cloud-Edge-End*", presents an innovative searchable encryption scheme named MSIAP that supports multi-keyword subset retrieval. The authors enhance the Apriori data mining algorithm to mine the relevance of files from massive information and construct a multi-level index structure to achieve efficient multi-keyword subset retrieval and dynamic update with minimal information disclosure in the smart grid. Furthermore, MSIAP strengthens existing data retrieval methods and significantly reduces the time complexity to accommodate the distributed smart grid system. The paper includes security analysis and performance evaluations by comparing the proposed method with existing works.

The seventh paper, authored by L. Sang et al. and titled "*Privacy-preserved Hybrid Cloud Framework for Real-time TCL-based Demand Response*", proposes a hybrid cloud framework for demand response programs based on thermostatically controlled loads (TCLs) that preserves users' privacy. The framework comprises users' clouds and aggregation clouds. Users' clouds store users' load profiles and use the proposed stable temperature-related response model to elicit users' temperature flexibility. Aggregation clouds aggregate users' flexibility based on individual users' fitting coefficients, utilize the slope-priority-based method for mean-variance analysis of aggregate flexibility, and propose an XGBoost-accelerated disaggregation model for selecting users in real-time. By separating flexibility eliciting models and aggregating methods into users' cloud and aggregation cloud, users' privacy is preserved. Numerical experiments demonstrate that the stable regression model achieves fewer prediction errors in users' cloud. Furthermore, in the aggregation cloud, the slope-priority-based method can achieve higher aggregate flexibility, and XGBoost-accelerated disaggregating reduces the solving time by nearly three orders of magnitude.

The eighth paper is titled "*Cloud-Edge Orchestrated Power Dispatching for Smart Grid with Distributed Energy Resources*" and authored by K. Wang et al. The paper proposes an energy-centric smart grid approach that utilizes cloud-edge computing to achieve power dispatching. Their solution includes energy caching and energy multiple addressing of the edge router, which helps to eliminate the intermittency of renewables and increase energy response speed. To ensure the stability of the energy market and encourage user participation in power dispatching, a cloud-edge computing-driven energy cache orchestration mechanism is also designed. Empirical results show that the response time is significantly reduced to meet the stringent quality of service requirements in a smart grid integrated with distributed energy resources.

The ninth paper is authored by B. Li et al. and titled "*Coordinated Cloud-Edge Anomaly Identification for Active Distribution Networks*". This paper presents an innovative method for anomaly identification in active distribution networks (ADN) based on a cloud-edge computing architecture to reduce the risks associated with ADN operations. The proposed method is designed to be widely applicable and efficient in identifying cyber or physical abnormalities. A hierarchical data flow architecture is developed to balance the timely and economical requirements of anomaly identification using coordinated cloud-edge computing. An integrated algorithm is also proposed based on the data flow architecture to identify anomalies with good robustness and accuracy, even under complex cyber-physical conditions. The numerical experiments demonstrate the superior performance of the proposed method over the state-of-the-art.

J. Zhong et al.'s article, entitled "*Enhancing Voltage Compliance in Distribution Network under Cloud and Edge Computing Framework*", is the tenth paper in the collection. The paper describes a cloud-edge computing-based framework that effectively manages a medium-voltage (MV) and low-voltage (LV) distribution network. The framework leverages the high computational efficiency of cloud computing and low data latency of edge computing to coordinate day-ahead and intraday operations across different layers. To predict both day-ahead and real-time load profiles, a customer-level forecasting algorithm is employed. An optimization model based on unbalanced-three phase optimal power flow is then proposed, and an efficient and accurate linearization-based approach is used to solve it, taking into account the controllability of online tap changers, distributed static var generator, and PV inverters. Simulations based on an extensive mocked MV-LV distribution network demonstrate the efficiency of the proposed method in enhancing voltage compliance by adopting the proposed forecasting method for real-time operations with high accuracy.

The eleventh paper, authored by N. Tzanis et al. and titled "*Cloud-edge architecture with virtualized hardware functionality for real-time diagnosis of transients in smart grids*", outlines a cloud-edge framework for efficient calculation of transient state estimation (TSE). TSE offers significant benefits, but requires high computational resources at the edge, close to measurement units, along with ultra-low latency communication. The framework offers TSE as a service by coordinating virtual machines (VMs) running on virtualized infrastructure and other non-virtualized physical nodes. To meet the stringent time requirements, part of the TSE is offloaded to dedicated hardware acceleration units (FPGA). The proposed TSE framework is validated using an IEEE 30-bus, and the results demonstrate superior total latency compared to conventional cloud and edge deployments.

The last paper in the collection is titled "*Cloud-Edge Hosted Digital Twins for Coordinated Control of Distributed Energy Resources*" and authored by J. Han et al. The paper addresses challenges in coordinating distributed energy resources (DERs) by proposing the application of digital twins (DTs), which can be hosted in the cloud for centralized control and at the edge for distributed control, reducing the need for real-time communication while achieving overall coordination. The proposed DT-based coordinated control is validated using a realistic real-time simulation test setup, and the results demonstrate significant improvement in the aggregated DERs' response, offering effective support to the grid during contingency events.

To conclude, we want to express our appreciation for the 12 papers that have been selected for this special issue, recognizing that they represent just a small portion of the vast research being conducted in the area of cloud-edge-end orchestrated computing for smart grid. We are grateful to the authors and reviewers for their invaluable contributions to this issue, and we want to offer a special thanks to Prof. Yuanyuan Yang, the Editor in Chief of IEEE Transactions on Cloud Computing, for her unwavering support and for giving us the opportunity to publish this special issue.

RUILONG DENG, *Guest Editor*
Zhejiang University
310027 China
dengruilong@zju.edu.cn

CHEE-WOOI TEN, *Guest Editor*
Michigan Technological University
49931-1295 USA
ten@mtu.edu

CHAOJIE LI, *Guest Editor*
University of New South Wales
2052 Australia
chaojie.li@unsw.edu.au

DUSIT NIYATO, *Guest Editor*
Nanyang Technological University
639798 Singapore
dniyato@ntu.edu.sg

FEI TENG, *Guest Editor*
Imperial College London
SW7 2AZ U.K.
f.teng@imperial.ac.uk

Ruilong Deng (Senior Member, IEEE) received the BSc and PhD degrees both in control science and engineering from Zhejiang University, Hangzhou, Zhejiang, China, in 2009 and 2014, respectively. He was a research fellow with Nanyang Technological University, Singapore, from 2014 to 2015; an AITF postdoctoral fellow with the University of Alberta, Edmonton, AB, Canada, from 2015 to 2018; and an assistant professor with Nanyang Technological University, from 2018 to 2019. Currently, he is a professor with the College of Control Science and Engineering, Zhejiang University, where he is also affiliated with the School of Cyber Science and Technology. His research interests include smart grid, cloud computing, communication networks, etc. He serves/served as an editor for *IEEE Transactions on Smart Grid* and *Journal of Communications and Networks*, and a guest editor for *IEEE Transactions on Emerging Topics in Computing* and *IET Cyber-Physical Systems: Theory & Applications*. He also serves/served as a Symposium Chair for IEEE SmartGridComm'19, IEEE GLOBECOM'21, etc.

Chee-Wooi Ten (Senior Member, IEEE) received the BSEE and MSEE degrees from Iowa State University in 1999 and 2001 respectively, and the PhD from University College Dublin (UCD), the National University of Ireland in 2009 before joining Michigan Tech in 2010. He is a professor of Electrical and Computer Engineering with Michigan Technological University. He previously worked as a power application engineer for Siemens Energy Management and Information System (SEMIS) in Singapore from 2002 to 2006. His research interests include modeling for interdependent critical cyberinfrastructures and SCADA automation applications for a power grid. He served as an editor for *IEEE Transactions on Smart Grid* and *Elsevier Journal Sustainable Energy, Grids and Networks (SEGAN)* and has authored a textbook titled "Electric Power: Distribution Emergency Operation."

Chaojie Li (Member, IEEE) received the BEng degree in electronic science and technology, the MEng degree in computer science from Chongqing University, Chongqing, China, in 2007 and 2011, respectively, and the PhD degree in electrical engineering from RMIT University, Melbourne, Australia, in 2017, where he was a research fellow for one and a half years. He was a senior algorithm engineer with Alibaba Group, Hangzhou, China. He is a senior research associate with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW, Australia. His current research interests include graph representation learning, distributed optimization and control in smart grid, neural networks, and their applications. He was a recipient of ARC Discovery Early Career Researcher Award in 2020 and selected as the Global Top 50 Chinese Young Scholars (in the field of AI+X) by Baidu in 2022.

Dusit Niyato (Fellow, IEEE) received the BE degree from the King Mongkuk's Institute of Technology Ladkrabang (KMITL), Thailand in 1999 and the PhD degree in electrical and computer engineering from the University of Manitoba, Canada in 2008. He is currently a professor with the School of Computer Science and Engineering and, by courtesy, School of Physical & Mathematical Sciences, the Nanyang Technological University, Singapore. He has published more than 400 technical papers in the area of wireless and mobile networking, and is an inventor of four US and German patents. He won the Best Young Researcher Award of IEEE Communications Society (ComSoc) Asia Pacific (AP) and The 2011 IEEE Communications Society Fred W. Ellersick Prize Paper Award. He will serve as the editor in chief for *IEEE Communications Surveys and Tutorials* in 2021-2022. He is also serving as a senior editor of *IEEE Wireless Communications Letter*, an area editor of *IEEE Transactions on Wireless Communications (Radio Management and Multiple Access)*, an associate editor of *IEEE Transactions on Communications*, *IEEE Transactions on Mobile Computing*, *IEEE Transactions on Vehicular Technology*, and *IEEE Transactions on Cognitive Communications and Networking*. He was a guest editor of *IEEE Journal on Selected Areas on Communications*. He was a distinguished lecturer of the IEEE Communications Society for 2016-2017. He was named the 2017, 2018, and 2019 highly cited researcher in computer science.

Fei Teng (Senior Member, IEEE) received the BEng degree from Beihang University, China in 2009 and the PhD degree from Imperial College London in 2015. He is currently a lecturer with the Department of Electrical and Electronic Engineering, Imperial College London. He is also serving as the deputy director of Imperial - Tsinghua Joint Research Centre for Intelligent Power and Energy Systems and holding a visiting position with MINES ParisTech, France. His research focuses on the optimization and data analytics for the efficient and resilient operation of cyber-physical power system.