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GUEST EDITORIAL

# Guest Editorial: Operational and structural resilience of power grids with high penetration of renewables

The switch to renewable power generation is promoted aggressively by government policies, growing investments, consumer preferences, and many other factors. However, high renewable penetration can impose significant challenges to designing and employing measures that enhance power grid resilience. Resilience has been posed as a requirement of increased criticality following severe phenomena and events (Texas freeze, California wildfires, India heatwaves, cyberattacks on power plants etc.) that go beyond electrical grid reliability. Dependence of renewables on climate and weather conditions and reliance on information and communication technologies complicate the challenge of accounting for them within grid resilience frameworks. Specifically, the asynchronous and limited-inertia characteristics of inverter-based resources can severely degrade the grid dynamic performance and shrink stability regions. Also, stochastic and intermittent nature of renewables requires the availability and fast response of flexibility resources and increases the computational complexity of decision-making problems, which will make methods for grid resilience even more challenging. Extensive behind-the-meter distributed energy resources further alter the behaviour of both distribution systems and transmission systems. Therefore, this Special Issue aims to address these challenges and key technologies for facilitating grid resilience in the pathway of grid decarbonization, with specific focus on operational and structural resilience of power grids.

This special issue presents 24 papers that investigate resilience issues of power grids with high penetration of renewables. The papers are grouped under the following topics: planning approaches boosting structural resilience, resilient operation strategies, inertia and frequency regulation challenges and methods, microgrid based resilience approaches, and novel methods for resilience analyses.

## 1 | PLANNING APPROACHES BOOSTING STRUCTURAL RESILIENCE

Ma et al., in their paper 'Allocation method of coupled PV-energy storage-charging station in hybrid AC/DC distribution networks balanced with economics and resilience', propose a bi-level optimization model for allocating PV-energy storage-charging stations in hybrid AC/DC distribution grids. Both economy and resilience objectives are considered and balanced. The results also demonstrate the advantages of using DC lines in faulty recovery.

Lu et al., in their paper 'A bi-level planning strategy of a hydrogen-supercapacitor hybrid energy storage system based on APA-MOHHO', present a method for planning a system consisting of a supercapacitor array and a hydrogen energy storage unit. Both energy management and capacity configuration are optimized. The results based on real-world data show that the proposed approach can mitigate power fluctuations, enhance capacity configuration accuracy and reduce the cost.

Niu et al., in their paper 'Resilient planning for high-renewable-integrated transmission systems under the impacts of ice storm disasters', propose a planning method considering the interactive effects of ice disasters on the grids' sources, networks and loads. They establish a two-layer mathematical model considering both resilience and economy objectives. Hierarchical reinforcement and generation protection are used as the resilient planning strategies.

Badi et al., in their paper 'Resilience-oriented expansion planning of multi-carrier microgrid utilizing bi-level technique', present a method for generation and transmission expansion planning. The resilience of coupled electricity and gas networks against floods and earthquakes is considered. A bi-level optimization approach is proposed, with the upper level minimizing the generation and transmission planning cost, and the lower level minimizing the expected annual operating cost considering natural disasters.

## 2 | RESILIENT OPERATION STRATEGIES

Fan et al., in their paper 'Mobile power sources pre-allocation and dispatch strategy in power-transportation coupled network under extreme weather', aim for efficient distribution grid fault recovery under extreme weather conditions. Incorporating the Dijkstra algorithm and blind number theory etc., the dispatch method adapts to dynamic information and makes decisions

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on loads restoration and mobile power sources routing, so as to improve the resilience of coupled power-transportation networks.

Zhao et al., in their paper 'A two-stage scheduling model for urban distribution network resilience enhancement in ice storms', propose a two-stage scenario-based distribution network optimization model, which ends up as a mixed integer linear programming model, for urban distribution grids resilience improvement against ice storms. The proposed method coordinates the routing of mobile de-icing equipment and the dispatching of distributed energy resources.

Rong et al., in their paper 'Coordination of preventive and emergency dispatch in renewable energy integrated power systems under extreme weather', propose a two-stage three-layer robust optimal dispatching model to coordinate preventive and emergency dispatch stages. A defender-attacker-defender approach is adopted, in which various dispatching measures are formulated as defenders, and the extreme weather event and wind power uncertainties are formulated as attackers.

Wu et al., in their paper 'Distribution network resilience enhancement strategy considering spatial–temporal migration of flexible resources on supply and demand sides', propose a spatial–temporal migration method for mobile power sources on the supply side, and internet data centres on the demand side. Power-transportation and power-computation coupling networks models are used. An optimization model maximizing grid resilience and minimizing dispatching costs is formulated.

Ju et al., in their paper 'Resilience enhancement strategy for cyber-physical distribution systems that considers cross-space propagation of information risk', analyse the interaction mechanism between the cyber space and physical space, and propose an information risk cross-space propagation model. An optimization strategy for information risk control is then established, to minimize the risk of coupling networks.

Li et al., in their paper 'A two-stage adaptive-robust optimization model for active distribution network with high penetration wind power generation', first present an adjustable box uncertainty set to feature the spatio-temporal correlation of wind generations. Then, they establish a two-stage risk-adjusted robust energy dispatch model for improving the operational resilience of active distribution networks.

## 3 | INERTIA AND FREQUENCY REGULATION CHALLENGES AND METHODS

Guo et al., in their paper 'Stochastic unit commitment for power systems with offshore wind farms towards frequency resiliency', incorporate the inertia support from offshore wind farms in their unit commitment model. The frequency constraint is captured using a multi-variative piece-wise linear function, and the frequency Nadir is also simulated considering varying inertia and disturbance conditions. A multi-cuts Benders decomposition algorithm is also proposed to solve the problem.

Xie et al., in their paper 'Research on load frequency control of multi-microgrids in an isolated system based on the multi-agent soft actor-critic algorithm', develop a load frequency control model for individual microgrids. The centralized training and decentralized execution multi-agent reinforcement learning approach and the multi-agent soft actor-critic algorithm are then used to design frequency control strategies for multi-microgrids.

Wang et al., in their paper 'Fuzzy model predictive control for frequency regulation of temporary microgrids during load restoration', propose an adaptive fuzzy model predictive control method for effective frequency regulation of temporary microgrids in the load restoration process. The regulation resources are coordinated by the fuzzy controller that provides weights of various regulation resources included in the model predictive control framework.

Im et al., in their paper 'Estimation of maximum non-synchronous generation of renewable energy in the South Korea power system based on the minimum level of inertia', determine the minimum inertia using the correlation between the available and required amount of inertia and governor resources considering the frequency standards in a South Korean power system. Therefore, they further estimate the maximum non-synchronous generation of renewable energy that can be accommodated.

Tabak et al., in their paper 'Maiden application of TID$^{\mu 1}$ ND$^{\mu 2}$ controller for effective load frequency control of non-linear two-area power system', apply the tilted integrated fractional derivative with filter plus fractional derivative controller to achieve load frequency control. The generation constraints and governor dead-band constraints are incorporated to evaluate the performance of the proposed control method.

Yang et al., in their paper 'Coordinated restoration of inverter-based power sources and synchronous generators for the high renewable penetrated power system considering the dynamic frequency regulation capability', combine frequency dynamics of inverter-based power sources and synchronous generators, and propose a coordinated restoration method. The dynamic frequency regulation capability is assessed using a unified transfer function structure model.

## 4 | MICROGRID BASED RESILIENCE APPROACHES

Sun et al., in their paper 'Digital twin-based online resilience scheduling for microgrids: an approach combining imitative learning and deep reinforcement learning', present a digital twin-based online resilient dispatch method for microgrids. They develop a hybrid sequential-parallel combination method of imitation learning and deep reinforcement learning for optimal scheduling. A mixed-integer second-order cone programming model is also proposed.

Fu et al., in their paper 'Market-clearing framework of a resilient microgrid with renewable energy considering emission reduction targets', look at an industrial park in China, and propose an internal market trading model considering both carbon emission reduction objectives and social welfare maximization.

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Zhang et al., in their paper 'A review on basic theory and technology of agricultural energy internet', investigate the basic theory and key enabling technologies of agricultural energy internet. They show that the agricultural energy internet framework has great potentials in realizing agricultural electrification and reducing carbon emissions from the agricultural sector.

Jing et al., in their paper 'Distributed dynamic event-triggered control for resilience-oriented current sharing in microgrid', propose a distributed dynamic event-triggered control method for mitigating the issues due to distributed renewables' stochastics and intermittency in microgrids. They aim to reduce the communication cost and achieve proportional current sharing among distributed generations. Standard linear heterogeneous multi-agent systems are also developed.

Kanwal et al., in their paper 'Artificial neural network assisted robust droop control of autonomous microgrid', propose a sliding mode robust droop control method based on the artificial neural network algorithm for islanded PV integrated microgrids. The droop response is governed using the swing equation. Their algorithms are trained and validated using real-world climate datasets.

## 5 | NOVEL METHODS FOR RESILIENCE ANALYSES

Lei et al., in their paper 'Adversarial false data injection attacks on deep learning-based short-term wind speed forecasting', propose an adversarial false data injection attack tactic for studying relevant cyber threats. They construct an optimization model to attain the optimal attack that would lead to the maximum prediction deviation if fed into the forecasting model.

Zheng et al., in their paper 'Probability confidence correlation analysis for many-objective optimal operation considering a set of conflict interests', propose a probability confidence correlation analysis method using a t-distributed stochastic neighbour embedding standard. Their method can preserve the distribution information and separability of the objectives. It can also aggregate and reduce the objective dimensions based on the importance sorting and objectives correlations.

Jin et al., in their paper 'A novel fault section location method for single pole to ground fault of DC distribution lines', propose a fault section location method for single pole to ground fault in DC distribution lines based on steady-state zero-mode current direction. They establish a unified zero-mode equivalent model for the DC distributed system in non-effectively grounded systems. They then propose a fault section location criterion based on the direction of the steady-state zero-mode current.

## 6 | SUMMARY

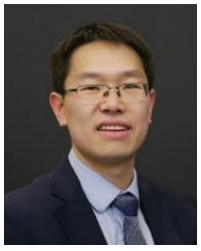
All the papers selected for this special issue show the related state-of-the-art research in power and energy communities. We expect that the special issue and its publications will trigger further research and technology innovation in those important fields. We would like to thank the reviewers for this Special Issue, for their dedication and hard work. We are also grateful to "IET Renewable Power Generation" Editor-in-Chief and the Editorial Office for their support throughout the editorial process.

## GUEST EDITOR BIOGRAPHIES

### Lead guest editors



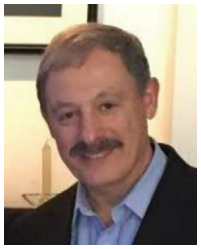
**Shunbo Lei** received the B.E. degree in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2013, and the Ph.D. degree in electrical engineering from The University of Hong Kong, Hong Kong SAR, China, in 2017. He was a Visiting Scholar with Argonne National Laboratory, Lemont, IL USA, from 2015 to 2017, a Postdoctoral Researcher with The University of Hong Kong from 2017 to 2019, and a Research Fellow with the University of Michigan, Ann Arbor, MI, USA, from 2019 to 2021. He is currently an Assistant Professor with the School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen, China. His research interests include power systems, resilience, grid-interactive efficient buildings, optimization and learning. He is the vice-chair for IEEE PES Loads Subcommittee, and the chair for IEEE PES Task Force on FlexGEB to Enhance Electric Service Resilience. He is also an Associate Editor for IEEE Transactions on Power Systems and IEEE Transactions on Smart Grid, and an awardee of the IEEE Transactions on Smart Grid Outstanding Paper Award, IEEE PES General Meeting Best Paper Award, and IEEE PES PCCC Outstanding Young Engineer Award.



**Yichen Zhang** received the Ph.D. degree in electrical engineering from The University of Tennessee, Knoxville, in 2018. He was also a research assistant with the Oak Ridge National Laboratory from 2016 to 2018. From 2018 to 2022, he was with the Energy Systems Division, Argonne National Laboratory. He is now an assistant professor at The University of Texas at Arlington. His research interests include power system dynamics, grid-interactive converters, renewable integration, control and decision-making for cyber-physical power systems. Dr. Zhang received the Best Reviewer Award for IEEE Transactions on Smart Grid in 2019, Best Reviewer Award for IEEE Transactions on Power Systems in 2020 and 2022, Argonne Impact Award from Argonne National Laboratory in 2021, and IEEE PES General Meeting Best Paper Award in 2022. He currently serves as the co-chair the IEEE task force on Flexible Grid-interactive Efficient Buildings to Enhance Electric Service Resilience from 2021, vice chair of IEEE PES Customer Systems & Smart Buildings Subcommittee, the associate editor for IEEE Transactions on Power Systems and IEEE Power Engineering Letters.

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## Senior guest editor



**Mohammad Shahidehpour** is a University Distinguished Professor at Illinois Institute of Technology (IIT). He also serves as the Bodine Chair Professor and Director of the Robert W. Galvin Center for Electricity Innovation at IIT. He is a Fellow of IEEE, American Association for the Advancement of Science, National Academy of Inventors, and Chinese Society of Electrical Engineering. Dr. Shahidehpour is an elected Member of the US National Academy of Engineering. He is listed as a highly cited researcher on the Web of Science (ranked in the top 1% by citations demonstrating significant influence among his peers).

## Guest editors



**Yunhe Hou** received the B.E. and Ph.D. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 1999 and 2005, respectively. He was a Post-Doctoral Research Fellow at Tsinghua University, Beijing, China, from 2005 to 2007, and a Post-Doctoral Researcher at Iowa State University, Ames, IA, USA, and the University College Dublin, Dublin, Ireland, from 2008 to 2009. He was also a Visiting Scientist at the Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, Cambridge, MA, USA, in 2010. He has been a Guest Professor with Huazhong University of Science and Technology, China from 2017 and an Academic Adviser of China Electric Power Research Institute from 2019. He joined the faculty of the University of Hong Kong, Hong Kong, in 2009, where he is an Associate Professor with the Department of Electrical and Electronic Engineering. Dr. Hou was an Associate Editor of the IEEE Transactions on Smart Grid from 2016 to 2021. Dr. Hou is currently an Associate Editor of the IEEE Transactions Power Systems and Journal of Modern Power Systems and Clean Energy.



**Mathaios Panteli** holds an Assistant Professor position within the Department of Electrical and Computer Engineering, University of Cyprus (UCY) since January 2021. He also holds an Honorary Lecturer position in Department of Electrical and Electronic Engineering, Imperial College London, UK, and he is currently an Andre Jaumotte Chair Professor in Université Libre de Bruxelles (by the Royal Academy of Belgium). Prior to joining UCY, he was a Lecturer at the Power and Energy Division of The University of Manchester, serving as the Deputy Lead of the Sustainable Energy Systems research cluster. His academic qualifications include an M.Eng. degree from Aristotle University of Thessaloniki, Greece, in 2009, and a Ph.D. degree in Electrical Power Engineering from The University of Manchester, U.K., in 2013. Through his academic career, Mathaios has successfully developed a multi-million research portfolio, attracting funding from research councils, industry, and European Commission. His main research interests include techno-economic reliability, resilience and flexibility assessment of future low-carbon energy systems, grid integration of renewable energy sources and integrated modelling and analysis of co-dependent critical infrastructures. He has published over 100 research articles in high-impact peer-reviewed journals and conference proceedings. Mathaios is an IEEE Senior Member, an IET Chartered Engineer (CEng), the Chair of the CIGRE working group C4.47 "Power System Resilience" and the CIGRE Cyprus National Committee, an invited member of multiple IEEE, CIGRE and CIRED working groups, and a Fellow of the Higher Education Academy (UK). He serves as an Associate Editor in IEEE Transactions on Sustainable Energy, IEEE Journal of Modern Power Systems and Clean Energy, and IET Renewable Power Generation. He is the recipient of the prestigious 2018 Newton Prize and he led the team receiving the 2022 Innovation Radar Prize by the European Commission.



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