Electrical Power and Energy Systems 154 (2023) 109439

Contents lists available at ScienceDirect

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Review

Guest Editorial: Special issue on flexible and resilient urban energy systems

Tao Jiang [a,*], Alessandra Parisio [b], Guodong Liu [c], Qianwen Xu [d], Qinglai Guo [e], Feifei Bai [f], Zakir Rather [g], Gengfeng Li [h], Vladimir Terzija [i]

[a] *Northeast Electric Power University, Jilin 132012, China*
[b] *University of Manchester, Manchester M13 9PL, UK*
[c] *Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA*
[d] *Royal Institute of Technology (KTH), Stockholm SE-100 44, Sweden*
[e] *Tsinghua University, Beijing 100084, China*
[f] *The University of Queensland, Brisbane, QLD 4072, Australia*
[g] *Indian Institute of Technology Bombay, Mumbai 400076, India*
[h] *Xi'an Jiaotong University, Xi'an 710049, China*
[i] *Newcastle University, School of Engineering, Newcastle Upon Tyne NE1 7RU, UK*

A B S T R A C T

This guest editorial summarizes the topics and the papers selected for the Special Issue on Flexible and Resilient Urban Energy Systems. After rigorous reviewing process, 21 papers are accepted for publication. These 21 accepted papers cover various aspects of urban energy systems and are distributed as following: situational awareness of urban energy systems (2 papers), quantification metrics of flexibility and resilience of urban energy systems (3 papers), vulnerability modeling of urban energy systems under various extreme events (3 papers), planning of flexible and resilient urban energy systems (4 papers), robust and resilient operation and control of urban energy systems (4 papers), recovery and restoration strategy of urban energy systems (2 papers), and coordination and interoperability of interconnected energy systems (3 papers). The Guest Editorial Board hopes this Special Issue can provide a valuable information for future research and advancements in the field of flexible and resilient urban energy systems.

1. Introduction

Urban energy systems are playing a critical role in enabling climate neutral and smart cities. Today's urban energy systems are facing more threats and challenges than ever from uncertain renewable power generation, fuel deliverability, natural disasters such as wildfires and hurricanes, cyber-attacks, and so forth. The integration of large amounts of small-scale distributed energy resources (DERs) such as rooftop photovoltaics (PVs), combined heat-power (CHP) units, and electric vehicles (EVs) further complicates the modeling and operation of urban energy systems. To achieve affordable, clean, and resilient energy supply to the city, there is an essential need to enable flexible and resilient urban energy systems (FRUES) through advancing fundamental operation and planning methodologies to improve the flexibility and resilience of energy infrastructures. This Special Issue is devoted to collect the state-of-the-art research to improve the flexibility and resilience of urban energy systems by addressing or minimizing the impact of multi-vector uncertainties, cyberattacks and natural disasters.

For this Special Issue, the Guest Editorial Board approved 21 papers for publication after rigorous reviewing process. The Guest Editorial Board would like to thank all the contributing authors for presenting their latest works in this Special Issue, and the anonymous reviewers for their valuable suggestions and constructive comments that have improved the quality of the papers collected here.

We wish to express our gratitude to the journal Editorial Board for providing us the opportunity to organize this Special Issue. In addition, we would like to thank the journal production team for their timely technical support from the call for papers, EVISE operation, and production of the accepted papers. It has been a great pleasure working with all of you on this Special Issue.

2. Review of topics addressed

The topics and the papers selected for this Special Issue are summarized in this section.

2.1. Situational awareness of urban energy systems

In order to achieve accurate and cost-effective household characteristic prediction without upgrading the existing advanced metering

* Corresponding author.
E-mail address: tjiang@neepu.edu.cn (T. Jiang).

https://doi.org/10.1016/j.ijepes.2023.109439
Received 3 June 2023; Accepted 3 August 2023
Available online 23 August 2023

infrastructure, a data-driven framework by integrating multiscale multivariate multifractal detrended fluctuation analysis, self-adaptive multifractal interpolation and mathematical morphological decomposition are proposed in [1]. The proposed framework is based on the multifractal characteristics of residential electricity consumption data recorded by smart meters. Meanwhile, such multifractal features are integrated with an advanced deep learning algorithm (Deep Forest) for household characteristic prediction. The case study using real-life smart meter data from Ireland shows that the proposed method has the potential to improve the accuracy of the household characteristic prediction and provides more thorough understanding of the relationship between energy usage profile and household characteristics.

As the data quality of distribution synchronized phasor measurements is very susceptible to newly emerging "Source ID Mix" data spoofing attacks, the authors in [2] propose a data-driven source authentication method to automatically identify the source information of distribution synchronized phasor measurements collected from multiple intra-state locations, thereby improving the reliability and cybersecurity of power systems. Then, an multi-weighted deep stacking forest with multi-weighted random scanning and a stacking structure is proposed to achieve strong representation learning capability and fast identification of the corresponding distribution synchrophasors source information.

2.2. Quantification metrics of flexibility and resilience of urban energy systems

Traditionally, N-1 security at peak load is treated as a rigid constraint in energy supply capability evaluation, which is not conducive to the effective utilization of equipment. A new evaluation method for the energy supply capability of regional electricity-heating energy systems, which models reliability as a flexible constraint and considers integrated demand response, is proposed in [3]. Based on the description of the maximum energy supply capacity through the boundary of the energy supply interval, a fast reliability evaluation method for operating points is proposed to quantify the load that the system can increase or need to reduce under certain reliability requirement.

To fill the gap in research on the resilience and dynamic behaviors of multi-decision complex interconnected energy systems under malicious attack, the authors in [4] propose a resilience evaluation method based on system dynamic theory to simulate the dynamic behaviors within and between systems under extreme events. In addition, a new resilience index framework is proposed based on the energy-coupling characteristics for complex energy interconnection system, which can depict the interactions among subsystems, such as damage propagations and feedbacks.

Considering difficulties in obtaining comprehensive operational data of millions of residential air conditioners and thermal data of buildings in actual power systems, it becomes a challenge to assess their available regulatory capacity. To address this challenge, a Gaussian Mixture Model-based evaluation method is proposed in [5] by utilizing partial easily observable data. Based on the thermoelectric models, a quantification method of the available regulation capacity is proposed, while ensuring a comfortable indoor temperature for all users. The case study of a demonstration project on demand response in China shows that the regulation capacity can be evaluated with more than 98% accuracy within 30 s, meeting application requirements of both day-ahead and intra-day dispatch.

2.3. Vulnerability modeling of urban energy systems under various extreme events

Aiming at high-impact and low-probability events such as ice disasters, which lead to significant losses of critical loads in urban distribution networks, the authors in [6] propose a multi-stage urban distribution network resilience enhancement framework to address the challenge of incomplete information. The typical failure scenarios are formed based on historical data of damages to electric components under ice disasters, and then distribution system operator designs a response plan and risk assessment for each scenario. If the risk is unacceptable for any period of the ice disaster, the distribution system operator revises the response plan to alleviate the "second-order" impacts.

High power grid-connected converters exposed to disturbances such as grid faults and cyber-attacks may pose enormous threats to the security of the power system. To address above issue, a thorough review of developed methods that describe the operational constraints and design the advanced controllers from resiliency perspective is presented in [7] to further compare and summarize the operational and corresponding analysis methods. Meanwhile, a flow limiting strategy based on multiple time scale operational regions is proposed to obtain an elastic converter taking full account of operational constraints.

Considering the cascading propagation and feedback mechanism of cross-space attacks in cyber-physical power systems, a network physical cross space attack model is formulated in [8] based on Markov process. Quantitative evaluation indicators of attack impacts are proposed as well. Using linear temporal logic, a formal axiomatic architecture for describing hybrid process triggered by attack events is proposed, where the tag transition semantics are applied to create formal specifications for system state transitions. In addition, a cross space attack scenario in 160-node cyber-physical power system test system is constructed using the event-driven model, in which the reachable regions and the evolution vector field are obtained as the formal analysis results of system state transitions.

2.4. Planning of flexible and resilient urban energy systems

As it becomes increasingly important for power companies to maintain uninterruptted service for critical loads and reduce the unserved energy for all loads, the authors in [9] introduce the background of resilient distribution systems and summarize resilient enhancement resources, operational mathematical models, and planning algorithms. In particular, the objective functions, mathematical formulas, decision variables, and solution algorithms of related research are compared and analyzed, through which the future research directions are proposed.

In recent years, natural disasters such as hurricane Katrina, or deliberate attacks on power systems, have highlighted the importance of resilient power distribution systems. In [10], a single-stage multi-criteria optimization model based on metaheuristic algorithms is proposed to maximize the resilience of a distribution system through various investment options, while minimizing the total cost incurred. The investment options are deployments of remotely controlled switches, installations of distributed energy resources and undergrounding of overhead lines. The case study shows how these different type of investments are prioritized and the importance of including managerial and logistic training in distribution companies to deal with extreme weather events.

As national authorities in many countries have been encouraging distribution system operators to develop plans to improve the network resilience to withstand natural disasters such as heat waves, an approach, compliant with the Italian performance-based regulation framework, is proposed to prioritize renovation actions on sections of electrical power distribution networks for improving resilience against heat waves in [11]. To estimate the reliability of network branches, an Accelerated Failure Time model is developed to encode the main covariates influencing the reliability behavior of network branches. Besides, the prioritization of renovation interventions is modeled using shortest path problem-based algorithm and Markov chain, which can identify the parts of the network that can generate the most benefits from refurbishment actions.

The strong thermoelectric coupling limits the feasible operating regions of CHP units, which leads to serious problems, such as wind curtailments and insufficient reserve capacity. To address this issue, the authors in [12] design a flexibility retrofit scheme for both inside and outside CHP units based on mature retrofit principles and develop a refined operation model for retrofitted CHP units. Meanwhile, a day-ahead optimal scheduling model considering chance constrained goal programming based reserve risk assessment is formulated to illustrate the advantages of the proposed retrofit scheme on operation and reserve flexibility. Numerical simulation shows the beneficial impact of dual heat storage on improving wind regulation and reducing storage risks.

2.5. Robust and resilient operation and control of urban energy systems

With the increase of renewable energy sources (RESs) in the district heating network, the temperature of the heated water tends to be disturbed, which calls for a deployment of thermal energy storage. To fill the gap in research on deployment of thermal energy storage, the concept and realization of a droop control for the district heating network is proposed in [13] to effectively exploit the flexibility of thermal energy storage. Considering the relationship between the temperature of the district heating water and the power sharing with other thermal energy resources, a mathematical model of regional heating network is established to mitigate the temperature deviations of district heating supply water.

The large-scale renewable energy integration introduces the challenge of frequency stability due to low inertia in weak power grids. To address this challenge, a semianalytical methodology considering time delays and ramping rate features is proposed in [14] to estimate the minimum required battery power reserve for preventing under-frequency load shedding when a severe generation trip occurs. The minimum reserve is derived from the time-variant kinetic energy of a given dispatch case. The case study on Mexican transmission system shows that the calculated battery power reserve can provide a cost-effective fast frequency response for a real islanded network.

To combine the rapid power adjustments of EVs with the large adjustment ability of generator sets, a real-time joint regulating reserve deployment model of EVs and coal-fired generators is proposed in [15] considering EV battery degradation under a two-stage Markov decision process. A piece-wise linear function based scalable approximate dynamic programming algorithm for different EV clusters is constructed to solve the real-time regulating reserve deployment model under uncertainties. Numerical simulation results on Henan power grid in China show that the proposed model can satisfy both the fast adjustment and the large energy support needs of the regulation.

Although successive linear programming is a practical method for solving large-scale nonlinear optimization problems, it is crucial to adjust the successive linear programming algorithm in order to achieve tractability. Combined with sequential linear programming algorithm, a modified successive linear programming algorithm is proposed in [16] to solve the alternating current optimal power flow problem, specified by the U.S. department of energy's grid optimization competition challenge. The proposed algorithm reduces search complexity by identifying the most influential constraints in nonlinear optimization problems that need to be watched during the solution process. Numerical experiments on test cases ranging from 500-bus to 30,000-bus systems show that the proposed algorithm is tractable.

2.6. Recovery and restoration strategy of urban energy systems

As large amounts of small-scale distributed generation can provide emergency power supply to critical loads during blackouts, a dynamic microgrids-based load restoration model is proposed in [17] for resilient operation of urban power distribution systems during outages considering uncertain RESs power outputs and loads as well as droop-controlled DERs. In addition, an offline probabilistic modeling and online updating method is proposed to characterize the time-varying uncertainty of multiple RESs power outputs and loads. The case study shows that the proposed uncertainty modeling and updating method as well as the dynamic microgrids can increase the overall system resilience.

To further ensure the sustainability of energy continuity to urban critical loads, the authors in [18] propose a resiliency improving mechanism for distribution systems, which not only detects location and boundary of load outages, but also meets the energy constraints and data sharing limitations to maximize resiliency. In addition, a weighted average consensus mechanism is proposed to detect failures due to faults or data loss and determine the isolated nodes. Simulation results demonstrate the effectiveness of proposed method in enhancing the distribution system resiliency by detecting failures and node isolation.

2.7. Coordination and interoperability of interconnected energy systems

The rapid uptake of natural gas-fired units in energy systems poses significant challenges in coordinating the electricity and gas systems. To address this challenge, a linear decision rule- based distributed adjustable robust optimal power and gas flow model is proposed in [19] for integrated electricity and natural gas system. Combining with the automatic generation control systems, an improved adjustable robust model is proposed to fully exploit its potential in mitigating renewable energy uncertainty. Based on two possible topological integrated electricity and natural gas system, i.e., with and without a central coordinator, two tailored alternating direction method of multipliers (ADMM) algorithms are proposed to preserve the information privacy and decision-making independence of subsystems.

As it is crucial for the reliable and efficient operation of interconnected power and natural gas systems to assess the status of natural gas networks when measurement information is insufficient, the authors in [20] propose an optimal scheduling method based on a multi-port gas network equivalent model, which is extracted from the real-time monitoring information. Based on this model, a two-way interconnected power and natural gas systems optimal scheduling strategy is proposed to minimize system operating costs and carbon emissions. The case study shows that the complexity of the model is reduced significantly without sacrificing the accuracy and robustness.

To fill the gap in research on traditional park level integrated energy system planning methods, which do not allocate reasonable equipment capacity based on the differences in load levels in different time sequences and stages, a multi-stage equipment capacity configuration planning model is proposed in [21] for park-level integrated energy system based on the concept of multistage planning, which can give better play to the advantages brought by the coupling effect of different stages. In addition, flexible loads are introduced to optimize the load curve structure, reduce the equipment capacity configured at each stage without disrupting the balance between energy supply capacity and load levels.

3. Closing remarks

In the context of enhancing operational flexibility and resilience of energy infrastructures to achieve affordable, clean and resilient energy supply to cities, data-analytic methodologies published in this Special Issue have clearly shown the superiority of new technologies such as recovery and restoration strategy as well as situational awareness, flexible planning and robust operation, which improve the flexibility and resilience of urban energy systems by addressing or minimize the impact of multi-vector uncertainties, cyberattacks and natural disasters.

For situational awareness of urban energy systems, there are several articles in this Special Issue reporting on new household characteristic prediction and data source authentication methods based on data-driven framework, which can improve the accuracy of the characteristic prediction and identify the source information automatically. The deep learning algorithms is further used to realize the accurate, economical, and efficient prediction as well as the rapid identification of source information. Future work may focus on more and diverse types of load profile feature extraction to improve the prediction accuracy of household characteristics. In addition, more and different types of measuring methods will be considered to verify the reliability and resilience of the proposed source authentication method.

For quantification metrics of flexibility and resilience of urban energy systems, new evaluation methods for the energy supply capability of urban energy systems are reported in this Special Issue considering the energy-coupling characteristics and integrated demand response for complex energy interconnection system. The future work will be focused on the coordination of the response strategies of subsystems, the matching degree of source and load in the system, and the effect of market mechanisms on resilience. The uncertainty of renewable energy generation and integrated demand response will also be further considered.

For vulnerability modeling of urban energy systems under various extreme events, the papers in this Special Issue propose multi-stage urban distribution network resilience enhancement framework to address the challenge of incomplete information, where the quantitative evaluation indicators of attack impact are used in response plan and risk assessment for each scenario. In the future, some intelligent methods will be exploited to form and select the failure scenarios while the necessary measurement set is considered to decrease the requirement of the data collection. Besides, the analysis of safe operation issues considering the interaction between multi-converters, the randomness of faults/cyber-attacks and the influence of the switching control will be further investigated.

For planning of flexible and resilient urban energy systems, there are several articles in this Special Issue summarizing the resilient enhancement resources, operational mathematical models, and planning algorithms comprehensively. Meanwhile, how these different type of investments are prioritized and the importance of including managerial and logistic training are studied to deal with extreme weather events. Future research directions includes the cooperative dispatch of mobile resources for systems restoration and the data-based algorithms for resilience-oriented planning problems as well as the optimal capacity configuration of thermal storage considering investment benefits in the urban energy systems.

For robust and resilient operation and control of urban energy systems, most of the researches in this Special Issue focus on the real-time regulating reserve deployment, which considers thermal energy storage, EVs and the minimum required battery power reserve. Other works focus on the modified successive linear programming algorithm. In the future, the optimal power reserve problem for multiple fast frequency response resources will be addressed, while the developed methods will be applied to large non-island power systems with high renewable penetration. In addition, the influences of EVs in dynamic transportation system will be considered.

For recovery and restoration strategy of urban energy systems, dynamic load restoration model and resiliency improving mechanism are reported for resilient operation of urban power distribution systems in this Special Issue considering small-scale distributed generation, load outage locations and data sharing constraints. In the future, the post-disaster repair process will be taken into account and the algorithms to improve the optimization efficiency will be particularly studied, while the normal operation reconfiguration, scalability, processing time and extension will be discussed for potential applicability of the proposed method in real feeders.

For coordination and interoperability of interconnected energy systems, most of the researches in this Special Issue explore the distributed adjustable robust optimal power and gas flow model for integrated electricity and natural gas system. On the basis of this model, the interconnected power and natural gas systems optimal scheduling strategy is proposed to minimize system operating costs. Future work will consider the impact of gas network delay on urban energy systems optimization. Meanwhile, solving the contradiction between conservatism and economy in robust optimization, and seeking a more suitable robust optimization model for urban energy systems will be one of the research directions.

The Guest Editorial Board hopes that the readers of this Special Issue find it as a valuable source of information for future research and advancement in the field of flexible and resilient urban energy systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] Cui Y, Yan R, Sharma R, Saha T, Horrocks N. Realizing multifractality of smart meter data for household characteristic prediction. Int J Electr Power Energy Syst 2022;139:108003.
[2] Cui Y, Bai F, Saha T, Yaghoobi J. Authenticating source information of distribution synchrophasors at intra-state locations for cyber-physical resilient power networks. Int J Electr Power Energy Syst 2022;139:108009.
[3] Ge S, Cao Y, Liu H, He X, Xu z, Li J. Energy supply capability of regional electricity-heating energy systems: Definition, evaluation method, and application. Int J Electr Power Energy Syst 2022;137:107755.
[4] Zhang Y, Liu W, Shi Q, Huang Y, Huang S. Resilience assessment of multi-decision complex energy interconnection system. Int J Electr Power Energy Syst 2022;137:107809.
[5] Hui H, Yu P, Zhang H, Dai N, Jiang W, Song Y. Regulation capacity evaluation of large-scale residential air conditioners for improving flexibility of urban power systems. Int J Electr Power Energy Syst 2022;142(Part A):108269.
[6] Wu Y, Lin Z, Liu C, Huang T, Chen Y, Ru Y, et al. Resilience enhancement for urban distribution network via risk-based emergency response plan amendment for ice disasters. Int J Electr Power Energy Syst 2022;141:108183.
[7] Zha X, Huang M, Liu Y, Tian Z. An overview on safe operation of grid-connected converters from resilience perspective: Analysis and design. Int J Electr Power Energy Syst 2022;143:108511.
[8] Qin B, Liu D, Chen G. Formal modeling and analysis of cyber-physical cross-space attacks in power grid. Int J Electr Power Energy Syst 2022;141:107790.
[9] Shi Q, Liu W, Bo Z, Hui H, Li F. Enhancing distribution system resilience against extreme weather events: Concept review, algorithm summary, and future vision. Int J Electr Power Energy Syst 2022;138:107860.
[10] Marcos FP, Domingo CM, San Román TG. Improving distribution network resilience through automation, distributed energy resources, and undergrounding. Int J Electr Power Energy Syst 2022;141:108116.
[11] Bellani L, Compare M, Zio E, Bosisio A, Greco B, Iannarelli G, et al. A reliability-centered methodology for identifying renovation actions for improving resilience against heat waves in power distribution grids. Int J Electr Power Energy Syst 2022;137:107813.
[12] Guo X, Lou S, Chen Z, Wu Y, Wang Y. Stochastic optimal scheduling considering reserve characteristics of retrofitted combined heat and power plants. Int J Electr Power Energy Syst 2022;140:108051.
[13] Lan T, Strunz K. Droop control for district heating networks: Solution for temperature control of multi-energy system with renewable power supply. Int J Electr Power Energy Syst 2023;146:108663.
[14] Alcaide-Godinez I, Bai F, Kumar Saha T, Castellanos R. Contingency reserve estimation of fast frequency response for battery energy storage system. Int J Electr Power Energy Syst 2022;143:108428.
[15] Xue X, Fang J, Ai X, Cui S, Xu M, Yao W, et al. Real-time joint regulating reserve deployment of electric vehicles and coal-fired generators considering EV battery degradation using scalable approximate dynamic programming. Int J Electr Power Energy Syst 2022;140:108017.
[16] Sadat SA, Sahraei-Ardakani M. Tuning successive linear programming to solve AC optimal power flow problem for large networks. Int J Electr Power Energy Syst 2022;137:107807.
[17] Lin C, Chen C, Liu F, Li G, Bie Z. Dynamic MGs-based load restoration for resilient urban power distribution systems considering intermittent RESs and droop control. Int J Electr Power Energy Syst 2022;140:107975.
[18] Abdelsalam AH, Eldosouky A, Srivastava AK. Enhancing distribution system resiliency with microgrids formation using weighted average consensus. Int J Electr Power Energy Syst 2022;141:108161.

[19] Zhai J, Jiang Y, Li J, Jones CN, Zhang X. Distributed adjustable robust optimal power-gas flow considering wind power uncertainty. Int J Electr Power Energy Syst 2022;139:107963.
[20] Huang H, Zhang A, Xu X, Li Q, Yang W, Qu G. Optimal scheduling of bidirectional coupled electricity-natural gas systems based on multi-port gas network equivalent model. Int J Electr Power Energy Syst 2022;139:108049.
[21] Xiong J, Sun Y, Wang J, Li Z, Xu Z, Zhai S. Multi-stage equipment optimal configuration of park-level integrated energy system considering flexible loads. Int J Electr Power Energy Syst 2022;140:108050.