Yuekai CHEN, Zhejing BAO, Miao YU, 2026. An approach to characterizing the power system security region by integrating distributionally robust optimization and Transformer-based deep learning. *ENGINEERING Information Technology & Electronic Engineering*, 27(5):260024.
https://doi.org/10.1631/ENG.ITEE.2026.0024

An approach to characterizing the power system security region by integrating distributionally robust optimization and Transformer-based deep learning

Key words: Security region; Distributionally robust optimization; Deep learning; Transformer model; Data-driven

Corresponding author: Zhejing BAO
E-mail: zjbao@zju.edu.cn
ORCID: https://orcid.org/0000-0002-8678-3805

Motivation

- Renewable generation and load uncertainty make it difficult for operators to clearly identify secure operating margins. Existing methods are limited by high dimensionality, heavy computational burden, and a trade-off between over-optimistic deterministic results and overly conservative robust results. To address these challenges, this study develops a distributionally robust optimization (DRO)- and Transformer-based approach for accurate, efficient, and uncertainty-aware security region characterization.

Main idea

- A DRO- and deep learning (DL)-based framework is proposed to characterize high-dimensional power system security regions under renewable generation and load uncertainty.
- A DRO-based active boundary point search strategy is developed to identify critical security boundary samples while balancing robustness and conservatism.
- A Transformer-based boundary fitting model is designed to capture global nonlinear dependencies among dimensions and reconstruct the continuous security region.

Method

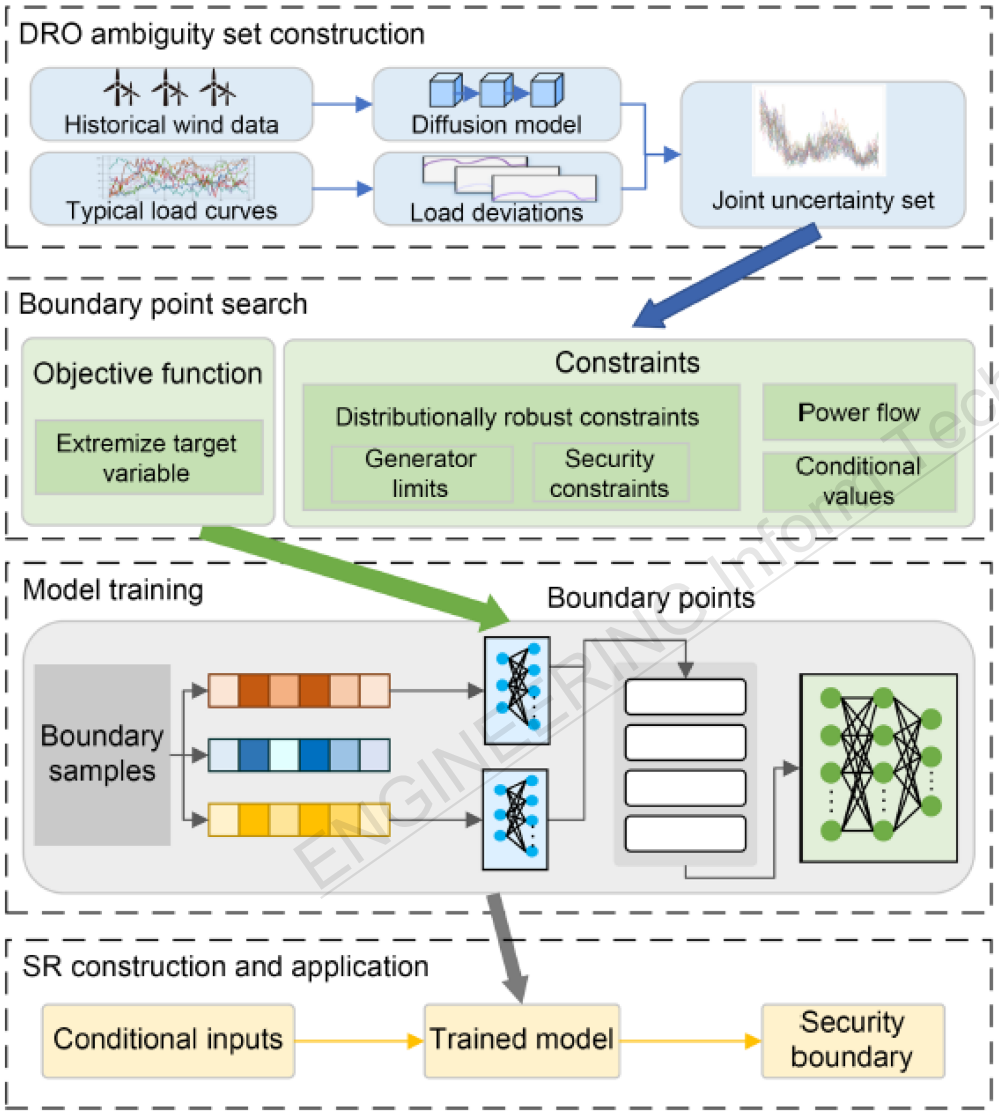

Fig. 1 Framework of the SR characterization by integrating DRO and DL

The proposed framework consists of four stages:

1. DRO ambiguity set construction
2. DRO-based boundary point search
3. Transformer-based model training
4. Security region construction and application

Method

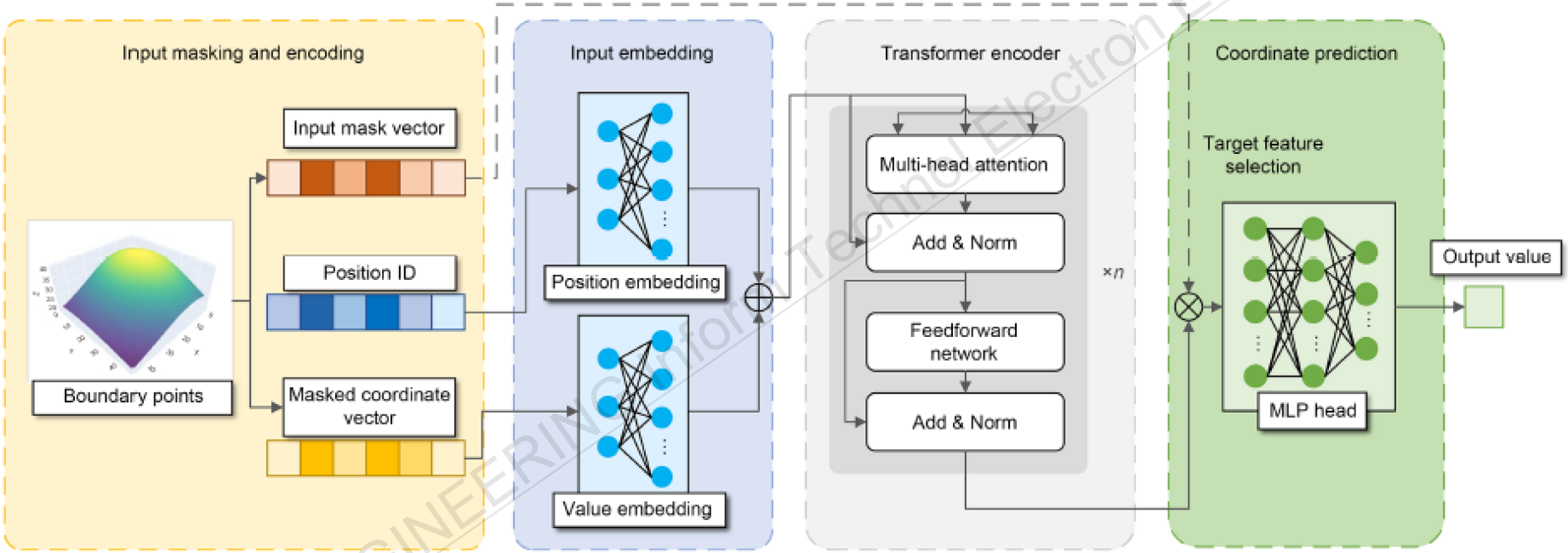

Fig. 3 Architecture of the Transformer-based SR boundary characterization model

Method

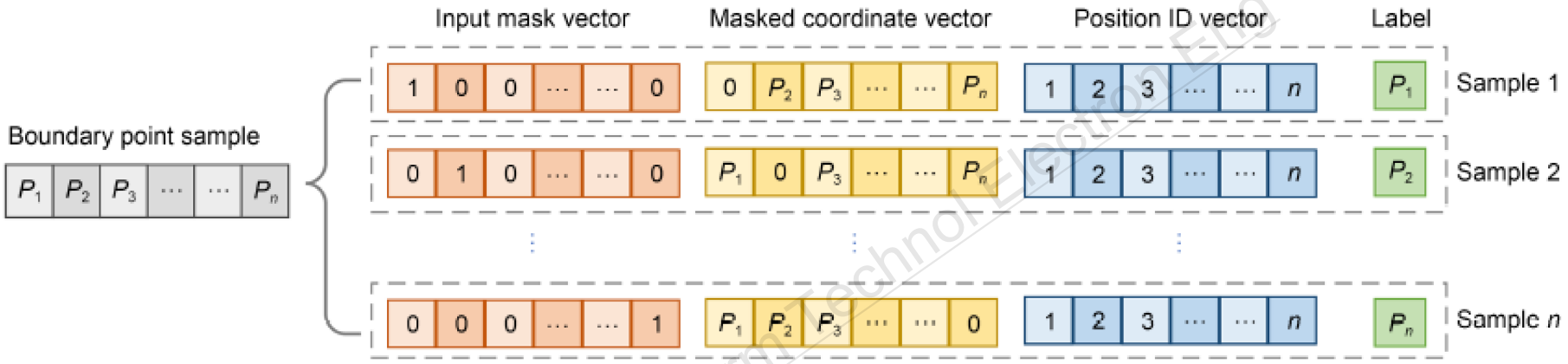

Fig. 4 Self-supervised sample augmentation and masking strategy

Boundary points are transformed into self-supervised training samples by masking one coordinate at a time. The Transformer encoder captures global nonlinear dependencies among dimensions, and the prediction head reconstructs the masked boundary coordinate.

Results

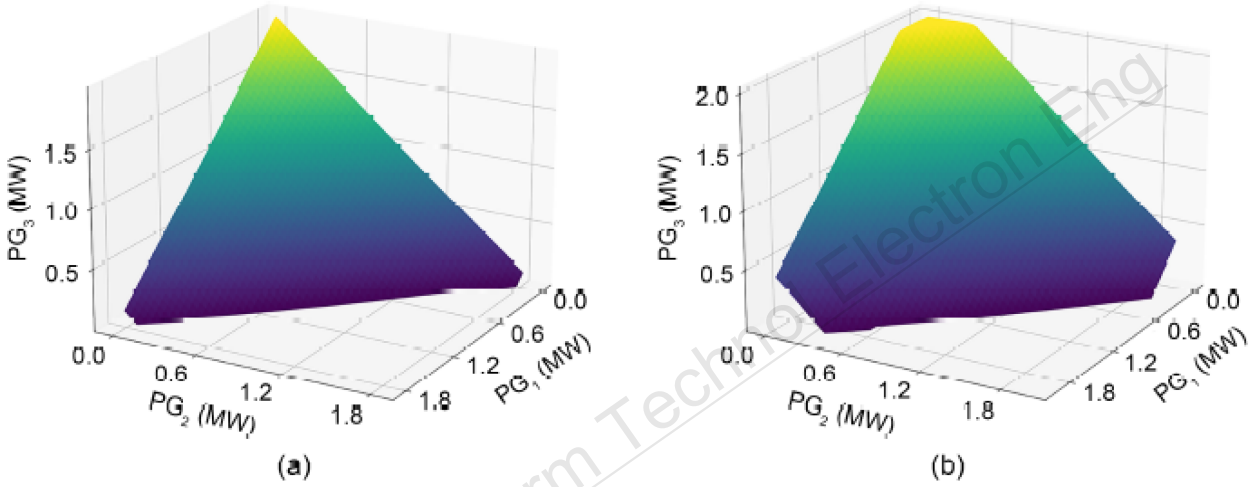

Fig. 8 Visualization of the constructed SRs: (a) IEEE 33-bus system; (b) IEEE 123-bus system

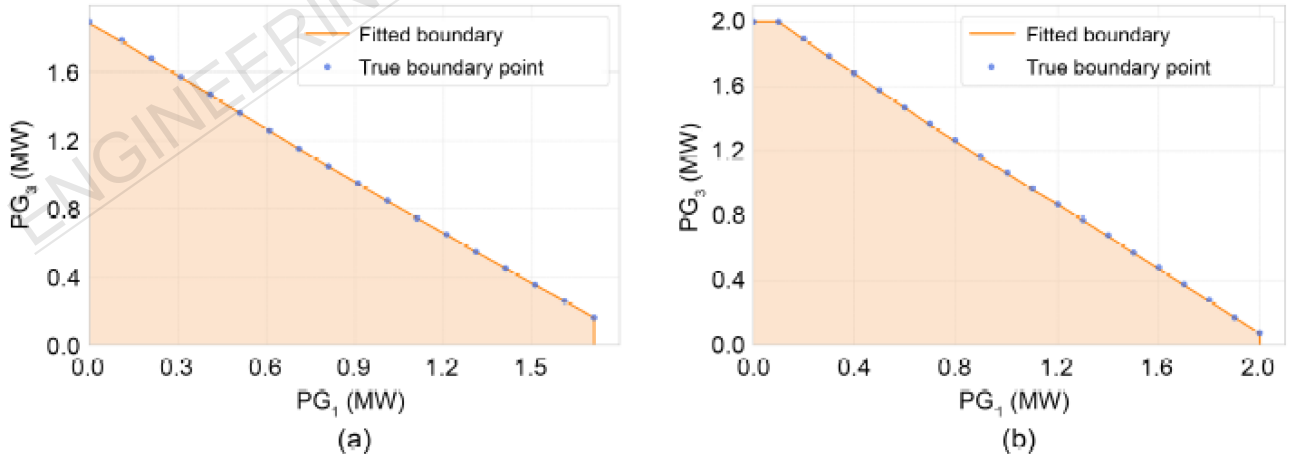

Fig. 9 Two-dimensional SR accuracy comparison: (a) IEEE 33-bus system; (b) IEEE 123-bus system

Results

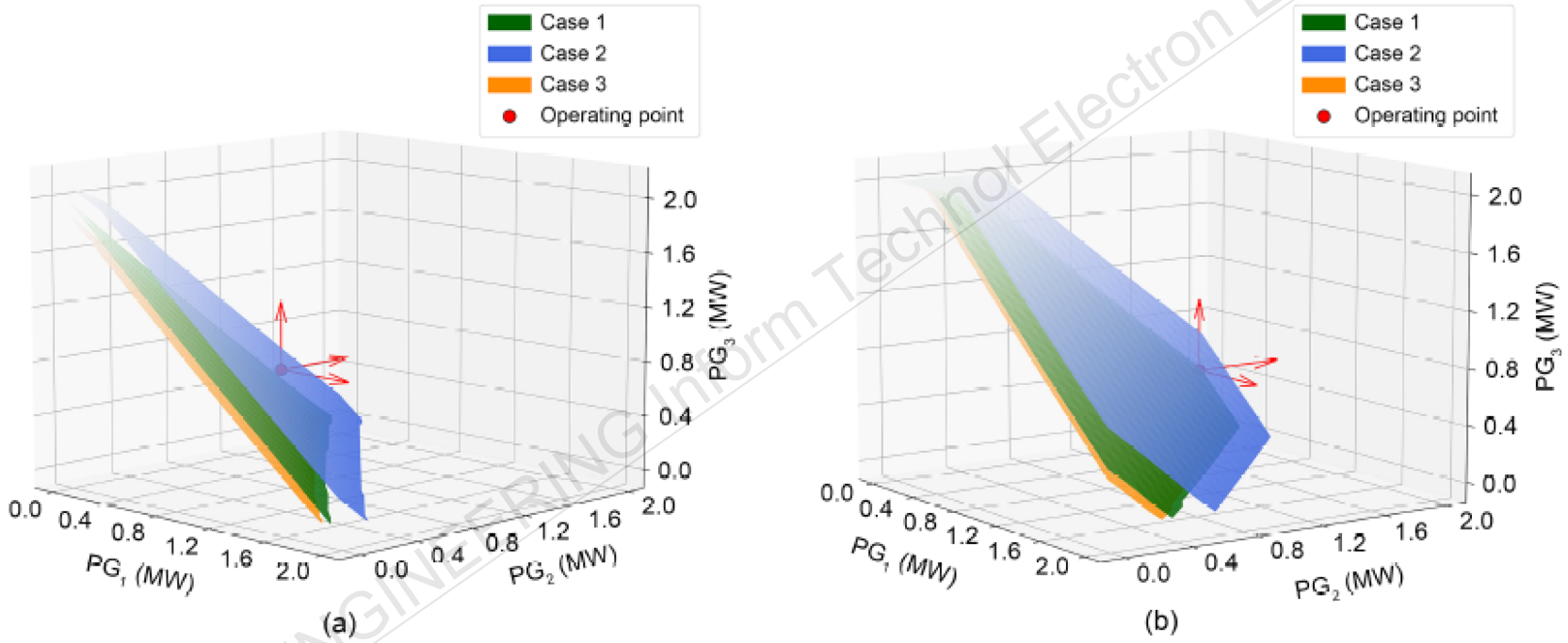

Fig. 10 SRs under different uncertainty handling approaches: (a) IEEE 33-bus system; (b) IEEE 123-bus system

Results

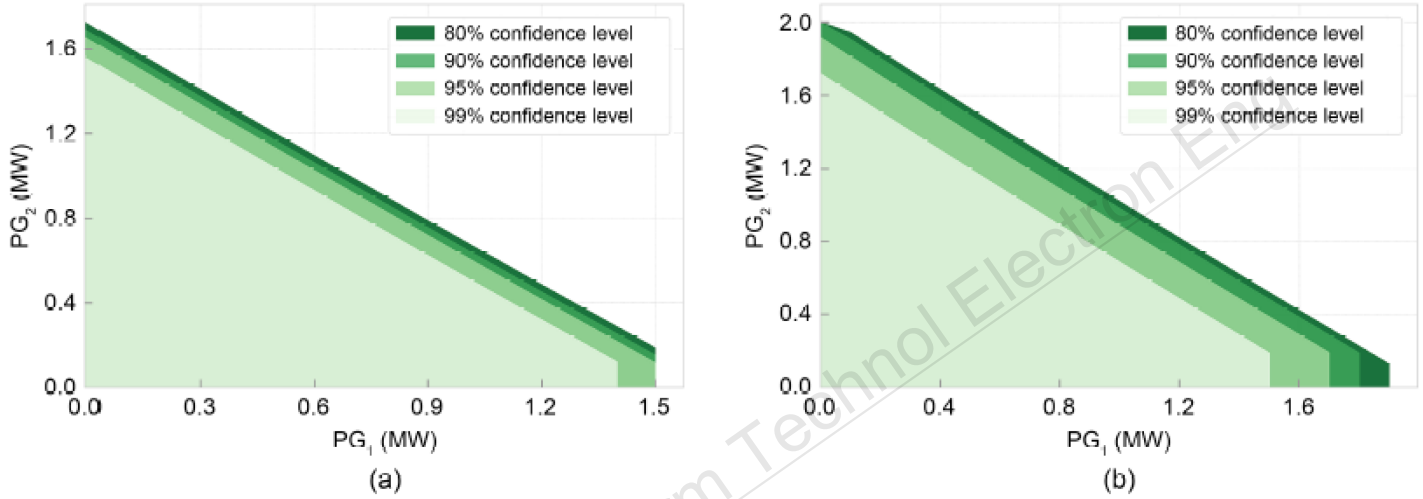

Fig. 11 SRs at different confidence levels: (a) IEEE 33-bus system; (b) IEEE 123-bus system

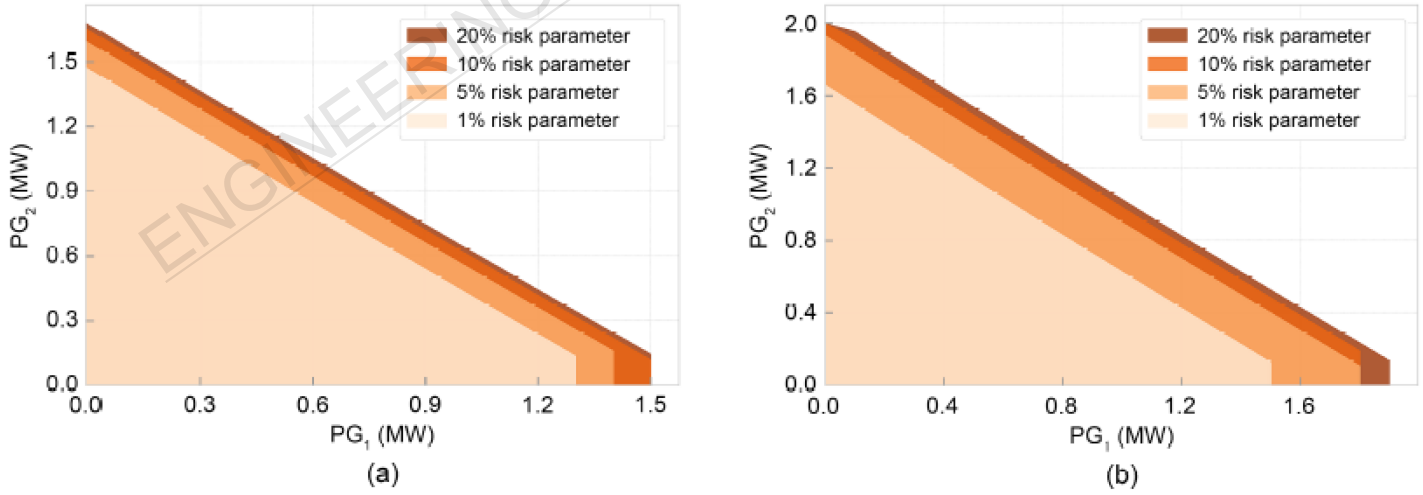

Fig. 12 SRs at different risk parameters: (a) IEEE 33-bus system; (b) IEEE 123-bus system

Conclusions

In this work, we propose a DRO- and Transformer-based approach for characterizing high-dimensional power system security regions under renewable generation and load uncertainty. The proposed framework accurately reconstructs security regions while balancing robustness and conservatism. Simulation results on IEEE test systems demonstrate its high accuracy, efficiency, and flexibility, providing a practical decision-support tool for power system security assessment under high uncertainty.

Yuekai CHEN received the B.S. degree in automation from the College of Electrical Engineering, Zhejiang University, Hangzhou, China. He is currently pursuing the M.S. degree in electrical engineering at the College of Electrical Engineering, Zhejiang University. His research interests include power system security analysis and data-driven security region characterization.

Zhejing BAO received the B.S. degree in 1996 and the M.S. degree in 1999 from Shandong University, Jinan, China, and the Ph.D. degree in control science and engineering from Zhejiang University, Hangzhou, China, in 2007. She is currently an associate professor at Zhejiang University. Her research interests include cascading failure mechanisms, reliability of complex power grids, and coordinated scheduling for integrated energy system.

Miao YU received the B.S. degree in automation in 2007 and the Ph.D. degree in control science and engineering in 2012 from Zhejiang University, Hangzhou, China. From 2013 to 2015, he was a postdoctoral researcher with Aalto University, Finland. He is currently a professor at Zhejiang University. His research interests include control strategies in microgrids and renewable power generation.