Distributed Control Strategies for Resilient Power Grid Operations: Advancing Smart Grid Resilience in the Era of Decentralization

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The global energy landscape is undergoing a profound transformation driven by the urgent need to combat climate change, the rapid advancement of renewable energy technologies, and the growing demand for reliable and sustainable electricity supply. This energy transition poses significant challenges to the operation and management of power grids, necessitating the development of innovative control strategies that can ensure grid resilience in the face of increasing complexity and uncertainty.

Distributed control strategies (DCS) have emerged as a promising approach to address these challenges by leveraging the inherent flexibility and adaptability of distributed energy resources and enabling more efficient and responsive grid operations. These strategies offer several key advantages in the following perspectives: *(i) dividing the control problem among multiple agents or nodes, making large-scale control and optimization feasible, (ii) naturally aligning with the decentralized architecture of modern smart grids that include various distributed components such as rooftop solar, battery storage, and electric vehicles, (iii) offering enhanced resilience by eliminating single points of failure and allowing the system to continue operating even if some nodes or communication links fail, and (iv) enabling the processing of data locally, reducing the need for centralized data aggregation and thereby enhancing privacy and security.*

In recent years, we have witnessed significant advances in distributed control theory and practice, enabled by integrating modern algorithmic, computing, and communication paradigms. These include data-driven and learning-based control, distributed optimization, consensus algorithms, and multi-agent reinforcement learning. At the same time, the increasing deployment of advanced metering infrastructure, phasor measurement units, and other smart grid technologies has dramatically improved the observability and controllability of power systems, generating enormous amounts of real-time data. However, the practical implementation of fully distributed control strategies in large-scale power systems is still in its early stages, hindered by technical, operational, and regulatory challenges. Therefore, this tutorial comes at a critical juncture, providing a timely and comprehensive overview of the state-of-the-art in DCS for power systems.

Our tutorial consists of five sections, each lasting 30-40 minutes and dedicated to the following topics: *(i) Introduction to Distributed Control in Power Systems, (ii) Foundations and Architectures for Distributed Control, (iii) Data-Driven and Learning-Based Approaches, (iv) Distributed Control for Resilience and Security, and (v) Benchmarks, Challenges, and Future Directions.* We focus on tailoring and analyzing DCS specifically for smart grid use cases such as real-time power flow optimization, frequency and voltage control, demand response, and DER coordination. The goal is to equip attendees with: (a) core distributed control algorithms and theory, (b) conceptual and technical know-how to address resilience and scalability challenges, (c) insights into integrating cutting-edge techniques such as data-driven control and reinforcement learning, and (d) major open issues around benchmarking, cybersecurity, and interoperability. By disseminating the state-of-the-art to researchers and practitioners, this tutorial aims to foster cross-disciplinary collaborations towards developing DCS for improved power grid operations in the net-zero era.

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