Abstract of Ph.D. Thesis

"OPF Frameworks for DSO Operational, Coordination and Market Models"

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Proliferation of distributed energy resources (DERs) in active distribution networks (ADNs) brings challenges for the distribution system operator (DSO) pertaining to their optimal scheduling, pricing, coordination among stakeholders, and market participation. This thesis addresses these critical issues by developing OPF-based optimization frameworks under different operating conditions. In this regard, a network-dependent, sensitivity-based, quadratic approximation of the branch-flow Distribution Optimal Power Flow (DOPF) model is proposed. This model is decomposed to compute active and reactive power distribution locational marginal prices (DLMPs), comprising incremental costs for energy, loss, congestion, and voltage components. These price signals vary according to the ADN operating conditions, thereby aiding DSO in incentivizing DERs for voltage support and congestion relief. Further, the proposed DOPF model is extended to incorporate the dynamic capabilities of heterogeneous DERs, enabling cost-benefit analyses for enhanced DSO operations. Moreover, the grid events arising from forecast errors and inherent uncertainties can result in load curtailment at the cost of economic losses and consumers' discomfort. To address this issue, an OPF-based electro-thermal DER scheduling framework within the integrated energy system (IES) is proposed. This supports resilient and economically efficient ADN operations, preventing it from collapsing or heavy load shedding during uncertain events.

Furthermore, the emergence of Distributed Energy Resource Aggregators (DERAs) to aggregate numerous small-scale DERs within ADN challenges their coordination with the DSO. To address this challenge, this thesis develops DER aggregation and DSO-DERA coordination under different market settings. A box polytope/ hyperrectangle-based geometric approach is proposed for characterizing DER flexibility. Using this method, the DERA aggregates operating regions of individual DERs through the Minkowski sum and submits a collective bid to the DSO. The DSO then performs an ADN-constrained optimization and sends disaggregated signals back to the DERA. This approach reduces the computational and communication burden of the DSO while empowering the DERA to distribute the schedules among its contracted DERs, thereby maximizing their benefits. With this approach, the DERA can operate at any point within the aggregated feasible region, ensuring compliance with ADN operational constraints. Furthermore, three DSO-DERA coordination frameworks for flexibility allocation under different market settings, i.e., joint, sequential, and independent, are proposed while ensuring ADN limits. The joint flexibility allocation (JFA) framework co-optimizes energy and flexibility markets. The sequential flexibility allocation (SFA) framework separates these markets via nodal price-based flexibility allocation, enabling flexibility evaluation by DERA. The independent flexibility allocation (IFA) framework evaluates nodal injection/withdrawal capabilities at DER nodes, facilitating autonomous DERA participation in local and wholesale markets without DSO interference.

In summary, this thesis provides a set of comprehensive tools and methodologies for the DSO and DERA to manage DERs, improving the operational and economic efficiency of ADNs. It offers scalable, market-integrated solutions that enhance DER participation in system services and electricity markets, supporting the transition toward a decentralized, resilient, and sustainable power system.