

Ph.D. DISSERTATION DEFENSE

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Title: Enhancing Power System Frequency Response with HVDC-
Connected Offshore Wind Farms: Adaptive Control and
Coordinated Optimization
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ABSTRACT

With the increasing penetration of wind energy into modern power systems, conventional synchronous generators are progressively displaced by converter-interfaced generation, resulting in reduced system inertia and weakened frequency response capabilities. As a prominent and rapidly growing source of wind power generation, offshore wind farms (OWFs) connected to onshore power grids through high-voltage direct-current (HVDC) transmission systems have significant potential to provide fast grid frequency support by utilizing their available kinetic energy and power reserves. Effective frequency support from OWFs is therefore essential to mitigate grid frequency deviations and enhance frequency stability of power systems with high wind power penetration.

However, several challenges hinder the effective utilization of OWFs for frequency support: (i) HVDC transmission systems electrically decouple offshore wind turbines (WTs) from onshore grid frequency dynamics, making conventional frequency-dependent control strategies difficult to implement without communication; (ii) heterogeneous operating conditions and limited energy reserves among individual WTs complicate the allocation of frequency support contributions, potentially leading to inefficient utilization of available support capacity and undesirable rotor speed recovery; and (iii) when multiple OWFs are interconnected through multi-terminal HVDC (MT-HVDC) systems, coordinating their frequency regulation contributions becomes increasingly challenging due to the interactions among offshore wind generation, MT-HVDC networks, and multiple onshore AC grids.

To address these challenges, this dissertation investigates adaptive control and optimal coordination strategies for frequency support from HVDC-connected OWFs at three different levels: (i) at the WT level, an adaptive fast frequency support strategy is developed for individual WTs, combining fuzzy-linear gain adjustment with an exponential rotor speed recovery mechanism to enhance frequency response while accounting for turbine heterogeneity; (ii) at the OWF level, a two-level control strategy is proposed to coordinate primary frequency support of WTs in an OWF, including a centralized model predictive controller to determine the wind-farm-level power reference, distributed WT-level controllers to allocate frequency support contributions according to their remaining extractable capacities, and an adaptive frequency support target adjustment mechanism to form the closed-loop between the centralized model predictive controller and distributed WT-level controllers for accommodating variations in available support capacity; and (iii) an optimal frequency regulation and power-sharing strategy is developed for multiple OWFs interconnected through MT-HVDC systems, which adopts a distributed primal–dual optimization approach to coordinate frequency regulation contributions between onshore grids and OWFs while utilizing HVDC voltage variations to exchange coordination information without direct onshore–offshore communication.

The effectiveness of the proposed strategies is evaluated through extensive simulation studies under different load disturbances, wind conditions, and system operating scenarios. The results demonstrate that the proposed control and coordination strategies improve system frequency response, enhance the utilization of available frequency support capacities, and facilitate coordinated power sharing among HVDC-connected OWFs. Overall, this dissertation provides a systematic investigation of frequency support from individual WTs to MT-HVDC-interconnected OWFs, contributing to the development of effective frequency support strategies for power systems with high wind power penetration.