Guest Editorial
Modeling and Advanced Control of Wind Turbines/Wind Farms

IN THE last decade, the utilization of wind power as a power generating source has grown exponentially. Since rich wind resources usually occur far from load centers, integrating large-scale wind power with a long-distance transmission system has become one of the most commonly used options in many areas of the world, such as Texas in the United States, the Three-North areas in China, and offshore wind farms in the North Sea. Under this scenario, wind turbine integration may suffer from a weak AC grid with small short-circuit ratio (SCR) and/or low system inertia. First, a low-SCR grid requires serious consideration of farm-/system-level interactions, such as resonances, instability on various spectrums of frequencies, etc. Second, different from the conventional thermal and hydropower generating units, the modern megawatt (MW) wind turbines with variable-speed operation are typically not very responsive to system frequency support. These characteristics significantly challenge the reliability and security of power systems with highly-penetrated wind power. The emerging control technologies promise power-electronic-interfaced wind turbines as well as large-scale wind farms to provide active and reactive powers to grids on a wide timeframe, as stabilizers of conventional generating units and the entire power systems.

This special section brings together papers focused on the recent advancements and breakthroughs in the technology of modeling and enhanced active/reactive power control of wind power conversion systems, ranging from components of wind turbines to wind farms. We have followed a two-tier review process. First, we have invited authors to submit extended abstracts for a preliminary review based on the scope of the special issue and abstract quality. Then, out of 92 submitted extended abstracts, the authors of 42 abstracts were invited for full paper submission. The submitted manuscripts underwent a formal review process, after which only 15 papers were accepted for publication. The accepted papers are broadly classified into two themes: i) modeling and stability analysis; and ii) advanced control and design. A brief discussion of each paper and the authors' contributions are presented below.

I. Modeling and Stability Analysis

The paper "Generic Dynamic Models for Modeling Wind Power Plants and Other Renewable Technologies in Large Scale Power System Studies" by Pourbeik *et al.* discusses the development, validation and implementation of public, generic and standard models for renewable energy systems that has taken place primarily in the Western Electricity Coordinating Council's Renewable Energy Modeling Task Force, over the past decade. The models, featured with a complex plant controller providing primary frequency response capability, can be quite useful for bulk electric system stability studies. Many improvements and additional features may yet remain to be developed, including numerical stability in low short-circuit ratio grid, new modules allowing for inertia based fast-frequency response emulation and parameterization based on disturbance data or measured factory tests.

The paper "Characteristic Analysis of Subsynchronous Resonance in Practical Wind Farms Connected to Series-Compensated Transmissions" by Xie *et al*. discusses, in a relatively more explicit and substantial way, the mechanism and characteristics of subsynchronous resonance (SSR) caused by the interaction of wind turbine generators (WTGs) with series compensation by analyzing the field data of 58 SSR events captured in a practical wind power system and examining the observed dynamics with previous theoretical results. It is found that the converter control of a doubly fed induction generator (DFIG) produces negative resistance at the slip frequency and thus causes unstable SSR, while the oscillation frequency keeps changing with the time, the variation of grid topology and the number of online generators.

The paper "Modeling and Stability Analysis of DC-Link Voltage Control in Multi VSCs with Integrated to Weak Grid" by Huang *et al*. discusses the stability of a DC-link voltage control affected by the interactions among wind turbines integrated to weak grid. A multi VSC model is presented for DC-link voltage control stability analysis considering the effect of interactions among VSCs, grid strength and operating point. Thanks to the model, self-interaction-impact components are presented to study the interactions between VSCs, and simulated results on a two-wind-turbine system validate the theoretical results.

The paper "Impedance Modeling of Three-Phase Voltage Source Converters in DQ, Sequence, and Phasor Domains" by Shah and Parsa discusses the impedance modeling of grid-connected VSC, with a specific focus on the effects of coupling between the ac and dc side networks and between the positive and negative sequence impedances. A modular modeling approach is presented by defining the VSC impedance as a three-by-three transfer matrix, which describes the VSC dynamics independent of the ac and dc side networks and captures the coupling effects in the off-diagonal elements. The relationships between the transfer matrix impedances in the dq, sequence, and phasor domains are presented, which are important to

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simultaneously utilize the advantages, and bridge the demerits, of the modeling and analysis in the different domains.

The paper "Modeling of DFIG-based WTs for Small-Signal Stability Analysis in DVC Timescale in Power Electronized Power Systems" by Hu *et al.*, based on the motion equation concept, discusses a dynamic modeling methodology of a DFIG-based wind turbine (WT) for small-signal stability analysis in a DC-link voltage control (DVC) timescale in power electronized power systems. The relationship between the active/reactive power imbalances and the phase/magnitude dynamics of the defined synthetic internal voltage (inner potential) vector are developed in the concerned timescale. With the developed model, characteristics of equivalent inertia, damping and synchronizing coefficients of DFIG WT in DVC timescale can be understood, and the dynamic interactions among multiple DFIG WTs, as well as between DFIG WT and other grid-connected devices in DVC timescale can be fully interpreted. Applications on the stability analyses of DFIG WT interconnected with VSC-HVDC system and two-DFIG WT system are taken as examples to validate the feasibility of the proposed model.

The paper "Stability Analysis of a PMSG Based Large Offshore Wind Farm Connected to a VSC-HVDC" by Kunjumuhammed *et al*. presents modal analysis of an offshore wind farm with PMSG type wind turbines connected to a VSC-HVDC. Multiple resonant frequencies are observed in the AC grid of offshore wind farms, and the characteristics of oscillatory modes are presented. Sensitivity of critical modes to wind turbine design parameters and their impact on closed loop stability of the system are discussed. It is found that robust control design is important for reliable operation of the system.

II. Advanced Control and Design

The paper "Combined Active and Reactive Power Control of Wind Farms Based on Model Predictive Control" by Zhao *et al*. discusses a combined wind farm controller based on Model Predictive Control (MPC) by considering the significant impact of active power on voltage variations due to the low X/R ratio of wind farm collector systems. Under the combined control, the Var capacity is optimized to prevent potential failures due to Var shortage, especially when the wind farm operates close to its full load. Two control modes are designed for both normal and emergency conditions, and the presented combined control scheme is verified by a wind farm consisting of 20 wind turbines.

The paper "Capacity Configuration and Coordinated Operation of a Hybrid Wind Farm with FSIG-Based and PMSG-Based Wind Farms During Grid Faults" by Yao *et al*. discusses a new capacity configuration method for the hybrid wind farm to calculate the required reactive power of a FSIG-based wind farm for the purpose of LVRT operation. Based on the capacity configuration result, the minimum installed capacity of a PMSG-based wind farm can be determined. Taking into account the impact of reactive power compensation capacity and grid transmission line parameters, the coordinated LVRT capability of the hybrid wind farm is then analyzed. Both simulation and experimental results are provided.

The paper "Fuzzy Logic Based Adaptive Droop Control in Multi-Terminal HVDC for Wind Power Integration" by Chen *et al*. discusses a fuzzy logic based adaptive droop controller for a multi-terminal DC (MTDC). This utilizes the available power capacity of the converters to update the droop coefficient, and can make a compromise between the dc voltage deviation and the power sharing. Moreover, the impact of the droop coefficient change on the stability of the MTDC grid is analyzed, and the effect of the dc-bus capacitor on the system dynamic is identified. Simulated results are provided to compare the proposed control strategy with the conventional one.

The paper "ESO-Based Inertia Emulation and Rotor Speed Recovery for DFIGs" by Liu *et al*. presents an inertial response control (IRC) technique to enable DFIGs to provide the power systems with controlled inertia in need by releasing energy to, or absorbing energy from, the system. An extended state observer (ESO) based inertia emulation controller (InEC) is designed, which is robust to measurement noise and changing working conditions. Meanwhile, an ESO-based RSRC is derived to mitigate potential adverse impacts of rotor speed recovery control (RSRC) of DFIGs on system frequency. Experimental results on a power hardware-in-loop testbed are provided to verify the proposed controllers.

The paper "Hybrid Modulated Active Damping Control for DFIG Based Wind Farm Participating in Frequency Response" by Geng *et al*. discusses the influence of the doubly-fed induction generator (DFIG) based wind farm (WF) participating in the frequency response (FR) on the oscillation modes of the power systems, while also proposing a hybrid modulated active damping scheme to mitigate the potential power oscillations. By integrating hybrid multiple active damping loops into the active and reactive power controller of the WF, respectively, the damping control on all the oscillation modes can be improved at the same time. The analysis and effectiveness of the proposed scheme are verified by the time-domain simulations on both two-area four-machine and IEEE 39-bus systems.

The paper "An Improved Method of DC Bus Voltage Pulsation Suppression for Asymmetric Wind Power PMSG Systems with a Compensation Unit in Parallel" by Hu *et al*. discusses an improved method of simultaneously suppressing the second harmonic DC-bus voltage pulsation and torque ripple by a compensation unit in parallel with the DC bus in the wind power permanent magnet synchronous generator (PMSG) system with asymmetric impedance. Compared to the existing methods, the proposed method uses fewer power devices and requires a much lower compensation current. The compensation's effectiveness is experimentally verified on a prototype asymmetric PMSG with inherent asymmetry and deliberately introduced asymmetries.

The paper "Cooperation-Driven Distributed Control Scheme for Large-Scale Wind Farm Active Power Regulation" by Gao *et al.* discusses a cooperation-driven distributed control scheme for wind farm active power regulation. Instead of competing with neighbouring controllers completely, the control strategy evaluates system-wide impacts of local control actions, and aims to achieve a coordinated control effect. In addition, the kinetic energy storage potential in a wind turbine is tapped to provide a buffer for power dispatch. Case studies demonstrate that a large wind farm can be effectively controlled to accurately track the demand power through the proposed control scheme.

The paper "Synchronization and Frequency Regulation of DFIG-Based Wind Turbine Generators with Synchronized Control" by Xin *et al.* discusses the synchronous stability of DFIG-based WTG with SYNC under frequency deviations by using the derived synchronization characteristics in $P_E - \omega_r$ plane. To solve the contradictory requirements on tuning the P-f droop coefficient when considering both synchronous and small signal stability, a modified SYNC is presented by firstly tuning the P-f droop coefficient to ensure the synchronous stability of the WTG under frequency deviation, and then by tuning the assistant damping coefficient to improve small signal stability. Simulated results on a 29-bus Hydro-Quebec transmission system with three DFIG-based wind farms are provided to verify the effectiveness of the analysis and the proposed control strategy.

The paper "New Control of Wind Turbines Ensuring Stable and Secure Operation Following Islanding of Wind Farms" by Erlich *et al*. discusses the voltage rise phenomena which the offshore wind farm experiences following the blocking of the high voltage direct current converter used for connecting the wind farm to the main onshore grid. It is found that the voltage rise is mainly caused by the integral characteristic of the classical current injection control. A new control scheme utilizing voltage injection is presented, which is not only suitable in offshore wind farms but in any other onshore applications. Simulated results are provided to validate the feasibility.

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