Guest Editorial for the Special Section on Enabling Very High Penetration Renewable Energy Integration Into Future Power Systems

I. Introduction

RENEWABLE energy such as wind power and photovoltaics (PV) is regarded as one of the main solutions to achieve power system sustainability. In recent years, renewable energy has been experiencing fast development. In 2016, 24.5% of the total power demand in the world was supplied by renewable energy, where 5.5% was produced by wind power and PV [item 1) in the Appendix]. It is estimated that by the end of 2017 the global wind power and PV capacity had reached about 565 GW and 335 GW respectively. Some power systems have already entered the era of high penetration of intermittent renewable energy integration. For example, over 22.4% of the total power demand was supplied by intermittent renewables in Spain in 2015. It is reported that on July 11, 2015, the wind power generation reached 140% of the whole country's demand in Denmark [item 2) in the Appendix]. In several provinces of China such as Gansu, Qinghai, and Xinjiang, the installed capacity of intermittent renewable energy has already occupied over 30% of the generation capacity [item 3) in the Appendix].

Countries around the world have set aggressive goals for high penetration of renewable energy in future power systems. The integration of high penetration of renewable energy will fundamentally change the configuration of power systems [item 4) in the Appendix]. The way that the power system balances the generation and load will change in both planning in a long-time scale and operation in a short-time scale, and in both transmission and distribution networks. The intermittency of renewables will raise power system security concern, ancillary services adequacy concern and economic issues. Hence, high penetration of renewable energy integration will bring significant challenges to future power systems. Failing to address these challenges may result in large amounts of wind power and PV curtailment and jeopardize the economics of renewable energy.

Different countries increasingly support projects in the research of high penetration renewable energy integration. Such as series studies at National Renewable Energy Laboratory (NREL) supported by Department of Energy in US, the research and innovation programme H2020 in European Union, and series of high penetration renewable energy projects in National Key Research and Development (R&D) Program of China. In 2016, the National Key R&D Program of China approved a project entitled *Fundamental Theory of Planning and Operation for Power Systems with High Share of Renewable Energy Generations* (under grant No. 2016YFB0900100). The overall objective of this project is to study the basic theory and method of planning and operation of high penetration renewable energy power systems and to provide standardized systems for a high share of renewable energy integration.

This Special Section is dedicated to providing innovative insights on future power systems accommodating high penetration of renewable energy. We followed a two-tier review process. First, about 300 two-page extended abstracts were received and were reviewed by the guest editorial board. Around 100 papers were invited for eight-page full paper submission. Finally, we accepted 24 papers in this special section. Since the challenges brought by high penetration of renewable energy are multifaceted, we group these papers into seven topics: 1) stochastic dependencies modeling; 2) power system forecasting; 3) power system flexibility; 4) transmission system related issues; 5) distribution system & microgrid operation; 6) power system frequency control; 7) power system oscillation analysis. A brief summary of these papers is presented in the following.

II. About the Papers

A. Stochastic Dependencies Modeling

The power system with high penetration of renewable energy integration faces great uncertainties in operation and planning. The dependencies among the uncertainties of the load and renewable energy have great impact on power system operation, stability, and power quality. However, accurate modeling and analysis of high dimentional dependencies are challenging because of the complexity in high dimensional probability space.

K. N. Hasan and R. Preece investigated the influence of stochastic dependence on the small-disturbance stability of the power system with high penetration of renewable energy [item 5) in the Appendix]. Global sensitivity analysis (GSA) was applied to identify and rank the critical uncertainties that most affect the damping of the most critical oscillatory mode. Results showed that Gaussian copula is the most suitable approach and has consistently low error even at higher levels of renewable energy penetration into the power system. X. Xu *et al*. performed a priority ranking of renewable energy variabilities that will affect the voltage stability of power systems also based on GSA [item 6) in the Appendix]. The stochastic response surface method (SRMS) improved the computation efficiency of the GSA based evaluation method. S. Pukhrem *et al*. proposed a Monte-Carlo simulation based probabilistic power quality (PQ) assessment method of the low voltage distribution network with high PV integration [item 7) in the Appendix]. The PQ impact metrics included small variations and abnormal events were assessed in terms of site and system PQ indices. Case studies

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showed that increase of PV integration results in high overvoltage risk and the PV integration can reduce the voltage unbalance as compared with no or low PV penetration.

B. Power System Forecasting

Centralized and distributed integration of renewable energy will aggravate the variabilities and nonlinear correlations of wind/solar resources in spatio-temporal scales, and thus pose issues in the forecasting of loads and renewable power generation.

Y. Wang *et al.* developed a data-driven probabilistic net load forecasting method specifically for a high penetration of distributed PV generation [item 8) in the Appendix]. Correlation analysis based on copula theory was conducted on the distributions and dependencies of the forecasting errors to generate a probabilistic net load forecast. Y. Chen *et al.* proposed a data-driven approach for scenario generation of renewable energy. Generative adversarial networks were used to capture renewable energy production patterns in both temporal and spatial dimensions for a large number of correlated resources [item 9) in the Appendix]. J. Yan *et al.* presented a multi-regional wind power forecasting method to capture the variable correlation of wind in NWPs. A multi-to-multi mapping network and ensemble stacked de-noising auto-encoder were used to provide a dependent forecast [item 10) in the Appendix].

C. Power System Flexibility

Lack of flexibility is one of the main reason of renewable energy curtailment. Defining, evaluating and exploring the flexibility of power system are able to help the accommodation of high penetrated renewable energy. Since the flexibility is not a quantity that can be directly measured and is usually understood from different perspectives, more in-depth studies should be carried out on this area.

Z. Lu *et al.* discussed the problem of power system planning with consideration of renewable energy curtailment [item 11) in the Appendix]. A probabilistic flexibility evaluation method was proposed which can reflect the direction, amount, frequency and consequence due to lack of flexibility. The proposed indices have a linear relationship with the renewable energy curtailment, so that the evaluation method can be conveniently applied in power system planning with very high penetration of renewables. X. Dui *et al.* proposed a two-stage method to determine the optimal power and capacity of battery energy system [item 12) in the Appendix]. The results showed how much capacity of battery energy system can optimally reduce the curtailment of wind and reduce the operation cost. F. Teng *et al.* analyzed the benefits of dynamic line rating in the transmission system [item 13) in the Appendix]. A scheduling model was proposed with consideration of multiple sources of uncertainty including wind generation, line ratings, and line outrages. The case study demonstrated the benefits of dynamic line rating in supporting cost effective integration of high penetration of wind generation.

D. Transmission System Related Issues

Great uncertainty and variability of renewable energy will more frequently and largely change the power flow pattern in the power system. More direct current (DC) lines also complexify the operation of transmission system. Accommodating such changes in transmission system operation and planning is a critical task since controllable elements in transmission side, such as transmission switching and DC system control, must be introduced under high renewable energy penetration. The conventional security constrained unit commitment, optimal dispatch, and reliability analysis must be reinvestigated.

J. Shi and S. S. Oren proposed a stochastic unit commitment model considering the topology control recourse for transmission switching [item 14) in the Appendix]. It was shown that transmission switching can not only reduce the objective value of direct current optimal power flow (DCOPF) when congestion exists but also reduce unit commitment cost when congestion does not exist. M. Zhou *et al.* developed a distributed dispatch approach for bulk AC/DC hybrid systems, where the day-ahead unit commit problem was decomposed into a master problem to determine the day-ahead transmission plan for high voltage direct current (HVDC) tie-line and various parallel sub-problems for regional dispatch [item 15) in the Appendix]. D. Apostolopoulou *et al.* examined the optimal dispatch for a cascade hydroelectric power system with consideration of the uncertainty of net load demand to maximize the head levels of each dam, and minimize the spillage effects [item 16) in the Appendix]. The power system reliability was addressed by M. Fan *et al.*, where a novel generation rescheduling algorithm was proposed to mitigate the variations of branch power flows and relieve the overload probability [item 17) in the Appendix]. The strong volatility of load and intermittent renewable generation may also lead to the tension of operating reserve. Y. Lin *et al*. proposed a multi-state model to quantitatively analyze the upward and downward reserve capacity of wind farms [item 18) in the Appendix].

E. Distribution System & Microgrid Operation

The introduction of high penetration distributed renewable energy integration, especially PV generation, brings bi-directional power flow and poses fundamental challenge on distribution system and microgrids. The problem of power economics, voltage control and stability analysis in low-voltage network should be re-defined and innovative methodologies are needed to address the emerging issues.

X. Yan *et al*. proposed a novel Locational Marginal Pricing (LMP) model of energy storage (ES) to reduce system congestion cost, where the pricing was derived by evaluating ES impact on the network power flows and congestions from the loss and congestion components in LMP [item 19) in the Appendix]. This work can further increase network flexibility and the capability of networks to accommodate increasing PV penetration. L. Wang *et al*. proposed a real-time PV inverter and battery energy storage system (BESS) coordinated control framework for voltage regulation of a weak distribution network with large-scale PV integration [item 20) in the Appendix]. The control strategy can help both utilities and PV owners for PV integration. Y. Chai *et al*. provided a double-layer voltage control strategy based on the distribution network partition [item 21) in the Appendix]. It combined the cluster autonomous optimization and distributed inter-cluster coordination optimization in different time scales. D. Choi *et al*. proposed a virtual multi-slack (VMS) droop control for the stand-alone microgrid [item 22) in the Appendix]. In the proposed control framework, one physical slack generator directly controls the magnitude and phase angle of its bus voltage and the other generators indirectly control the magnitudes and phase angles of their bus voltages by using the

VMS droop control. It results in the proper load sharing between the generators. Y. Li *et al*. presented a formal analysis for the stability assessment of the networked microgrids with high penetration of distributed energy resources (DERs) [item 23) in the Appendix]. The analysis with mathematical rigor directly computes the bounds of all possible dynamic trajectories and provides stability information unattainable by traditional time-domain simulations or direct methods. Results showed that the analysis can efficiently evaluate the impacts of disturbances on networked microgrid dynamics and how far the networked microgrid system is from its stability margins.

F. Power System Frequency Control

Under the high penetration of renewable energy, the power system suffers from low inertia and deteriorated frequency performance. Therefore, wind power and PV are supposed to have responsibility to provide frequency response similar to a conventional synchronized generator.

D. Yang *et al.* proposed a temporary frequency support scheme of doubly fed induction generator (DFIG) that can improve the frequency nadir while ensuring rapid frequency stabilization. According to the analysis and test results, the proposed scheme is able to improve the frequency response particularly for high wind power penetration levels [item 24) in the Appendix]. Y. Liu *et al.* assessed the frequency response of U.S. power grid with an industry-provided full-detail interconnection model [item 25) in the Appendix]. The paper also discussed the practical solutions to address the declining frequency response in the U.S.

G. Power System Oscillation Analysis

Power electronic converters and the use of AC/DC grids have been increasing with more and more renewable energy being integrated into power systems. The dynamic interaction between the AC/DC grid and power electronic converters makes the oscillatory stability analysis much more complex.

J. Ying *et al.* studied the impact of inertia control of DFIG-based wind turbine on electromechanical oscillation damping via a linearized model of wind turbine [item 26) in the Appendix]. Through the analysis, the cause and effect of oscillation damping were explained from a general perspective. C. Liu *et al*. proposed a line modal potential energy (LMPE) method for the inter-area oscillation analysis and damping control of DFIG from the network perspective [item 27) in the Appendix]. The proposed method can be used for sub-mode analysis and oscillation suppression. H. Liu *et al*. presented the concept of unified *dq*-frame impedance network model (INM), with which different converters, as well as traditional generators and HVDC, can be incorporated to form an integrated *s*-domain model of a practical system [item 28) in the Appendix]. And then, a new criterion is proposed to quantify the oscillatory stability by analyzing the frequency characteristics of the determinant of the matrix.

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Appendix
Related Work

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