Preface

Power systems are currently undergoing significant changes. Support for environmental protection and advocacy of sustainable economic development have led to a rapid growth of renewable energy-generating capacity in recent years, primarily in the form of wind and solar generation resources. Wind and solar power can provide huge benefits since they are plentiful, widely distributed, and clean. The massive deployment of these renewable energy resources also drives their per-unit cost down so that wind and solar power can now compete in the marketplace with conventional energy production. Power system operators will inevitably face challenges in adapting to this environment.

Wind and solar energy resources exhibit notably different characteristics from their fossil fuel-burning counterparts. Since the output of wind and solar generators is variable and uncertain across multiple timescales, they are often referred to as variable energy resources (VERs). Numerous integration studies and operational experiences have implied that as a large amount of VERs is integrated into an electric grid, it could fundamentally change how the grid is planned and operated. Thus, grid operators are concerned with the economics and reliability of a power grid where VERs are added. To overcome this concern, successful solutions have been developed to mitigate the adverse effects brought to the grid by the VERs. The operational experiences gained worldwide also provide useful guidance to renewable integration. However, most of the past efforts were focused on studies assuming a low or medium penetration level of VERs. Due to the assumptions made in these studies, some integration issues may not manifest themselves if the penetration level of VERs is not high enough. The issues associated with integrating VERs are also complicated and multifaceted, spanning from long-term planning to short-term operations. This requires comprehensive studies to be performed to ensure that the whole spectrum of issues is examined. Today, interconnection studies of VERs are evolving at a fast pace, and the focus is on scenarios with a high penetration level of VERs.

As we continue on the path of increasing the installed capacity of renewable electricity, many areas that have set goals to incorporate high levels of VERs in their power systems are quickly approaching those penetration levels. For example, electricity from renewable energy resources will account for 33% of total consumption in California by 2020. The Danish government aims to be fully independent of fossil fuels by 2050. When the penetration level of VERs is high, a large amount of conventional generators could be displaced from dispatch. As a result, if no significant changes are introduced to the grid, there may be a limit on the maximum amount of VERs that can be added to the grid while maintaining reliability. This limit depends on the size of the grid as well as the location and diversity of VERs. Beyond this limit, the installation of more VERs will not be effective or reliable unless those issues, which are an obstacle to the interconnection of VERs at a large scale, can be effectively mitigated. Some of these mitigations are physical in nature, while others are institutional.

As a first step to solve these issues, a thorough understanding of the technical challenges which could arise is a prerequisite to the successful integration of large-scale VERs into bulk power systems.

The first challenge in the integration of a large share of VERs into a grid is the need to upgrade the transmission network, i.e., to build long and often expensive transmission lines. These new transmission lines are necessary to transfer the power from wind/solar farms, usually in remote, low population areas, to high load locations. Otherwise, wind/solar power has to be constrained to below its full capacity, which leads to a waste of energy that could be produced. However, both the high cost and the long construction time could discourage such development of a new transmission network. Moreover, uncertainty of regulatory policies makes it hard to decide when to expand the transmission network's capacity and what the efficient capacity is. Since the installation of VERs can occur at unprecedented rates, building new transmission lines could significantly lag behind renewable resource development as has often been experienced in areas with high concentrations of VERs.

The second challenge associated with accommodating large-scale VERs is that it becomes necessary to increase system flexibility in order to maintain a generation–load balance in power system operations. Flexibility is the capability of a grid to respond to changes in load and variable generation. This flexibility difficulty arises because VERs possess two major attributes that notably impact the bulk power system's planning and operations. The first is variability—the output of variable generation changes according to the availability of the primary fuel (wind, sunlight, and moving water), resulting in fluctuations in plant output on all timescales. The second is uncertainty—the magnitude and timing of variable generation output is less predictable than for conventional generation.

Instantaneous electrical generation and consumption must remain in balance to maintain grid stability. Despite many years of experience that have been acquired by utilities to manage the variations from load, the variability, and uncertainty contributed from VERs will make the balancing task much harder. Numerous options have been proposed to increase the flexibility of a power grid, which fall into two categories: physical flexibility and institutional measures. For instance, more flexibility can be physically obtained by adding more responsive resources, using smart grid strategies, or reducing demand when wind production is high.

Institutional measures can include improving wind and solar forecasts, exporting and importing power to neighboring areas, and designing new market mechanisms to incentivize the provision of flexibility. Insufficient flexibility will result in an unsatisfactory frequency control performance or curtailment of power from VERs. Since a high penetration of VERs will eventually deplete the responsive capability of physical resources in a grid, adding more flexibility may come at a significant cost and it may take a long period of time to plan. A cost-effective portfolio for the provision of flexibility is a necessity in order to prepare for a future grid with a large amount of VERs.

The third challenge is the impact of VERs on the dynamics of a power grid where they are present. Different types of generators behave distinctly during grid disturbances. Today, most wind turbines use variable speed generators combined with partial- or full-scale power converters between the turbine generator and the collector system, which generally leads to more desirable properties for grid interconnection such as low-voltage ride through capability. Simulation results have shown that the transient stability for a power system with up to around 30% share of VERs is not a limiting factor. However, VERs have low short circuit ratio and do not contribute to the system's synchronous inertia since they are based on power electronics devices. As they displace a large share of synchronous machines in operations, it dramatically changes the dynamic characteristics of the grid, thus necessitating a need to study the dynamic impact of VERs on power systems. The low short circuit ratio could reduce the strength of the system where dynamic voltage support is crucial. Depending on the size of the system, frequency stability may be problematic if the frequency declines quickly enough to cause a cascading effect following the trip of a large generator unit. Therefore, all of these aspects need to be evaluated to ensure predictable, stable behavior during system faults when the penetration level of VERs is extremely high. The industry is also developing a new concept of essential reliability services as a necessary and critical part of the fundamental reliability functions to the grid reliability. Two examples of essential reliability services are voltage support and frequency support, which are both strongly affected by significant increases in the share of VERs.

The fourth challenge is managing large shares of VERs in a power market context. This requires coordination of scheduling processes across multiple time-scales and new market design to improve market efficiency and provide incentive to resources to provide reliability services. The VER forecast is one of the most cost-effective tools in system operators' control rooms to integrate renewable resources. The accuracy of variable generation forecasting has been steadily increased thanks to the improvement in both the numerical weather models and the statistical models used, as well as the geographic diversity of VERs which reduces the fluctuations in their power production. A power grid can see tremendous benefits in both economics and reliability from a well-functioning VERs forecast because it allows conventional resources to be committed and dispatched more efficiently.

In addition to the VER forecast, the reserves carried by the grid also play an important role in improving market efficiency. The actual power production from

VERs can sometimes deviate from their forecast due to their variations and uncertainties. When this happens, it can be managed through deployment of reserves allocated in advance. Reserves that are used in cases of large generating unit failures or load fluctuations may also be used to compensate for the variability and uncertainty of VERs. Determining required reserves highly depends on the operational policies and the response time of the reserve. It is generally agreed that more reserves are needed as the penetration level of VERs increases. As the economic implications of increasing reserves become more significant, some approaches have been proposed to maintain balance between reliability and efficiency. An excessive amount of reserves will reduce market efficiency while an insufficient amount of reserves is detrimental to reliability. Some approaches proposed include introducing a balancing market, sharing reserves among a larger footprint, and clearing the market through stochastic/robust optimization. The creation of a larger market can reduce the total requirements for reserve capacity due to geographic diversity of load and VERs, and thus saves operational cost. The exchanging and sharing of reserves between neighboring systems also introduces an increase in efficiency since less-expensive resources outside of a given balancing region is accessible by this region. The European Network of Transmission System Operators and the energy imbalance market (EIM) in the western US are such examples.

Recent work has shed some light on how to overcome these challenges in the context of a high penetration of VERs. From the encouraging results obtained from these studies, a high penetration of VERs is both technically feasible and economically viable for a future power grid.

This book will provide a thorough understanding of the basic aspects that need to be addressed for both system planning and operation at a high penetration of VERs as well as describes the most recent development of innovative technologies and cutting-edge research to address these challenges. Both system planning and operations are the key factors for a successful VER integration. Well-developed system planning can reveal the trend of the reliability issues that will grow over time, and it allows the most cost-effective long-term solutions to be implemented before these issues become prominent. Effective system operation can handle the challenges as they unfold and thus quickly improve the system's capability to integrate VERs. This book will focus on both and provides international experiences to demonstrate the advantages of the latest developments in system planning and operation in the areas of renewable integration.

This book covers a variety of subjects associated with the interconnection of VERs and presents a number of comprehensive and practical solutions which summarize the best practices and case studies for three power grids where a large amount of VERs are already present: Texas, Germany, and China.

This book also emphasizes the interrelation between the economic aspects, reliability, and policy development of renewable integration since any successful strategies that help improve the security of a future grid with VERs present have to be cost-effective, and the enhancement of these strategies need to be supported by the regulatory agencies in charge of the grid security and reliability.

This book could be useful for engineers and operators in power system planning and operation, as well as academic researchers. It can serve as an excellent introduction for university students in electrical engineering at both undergraduate and postgraduate levels. The dissemination of the knowledge contained in this book can stimulate more ideas and innovations to be developed and eventually help to facilitate the interconnection of more VERs in the future grid.

This book is divided into ten chapters.

Chapter 1: "Wind Integration in ERCOT" discusses the challenges and solutions associated with the integration of large-scale wind generation in the Electric Reliability Council of Texas (ERCOT) system. It details the factors that have contributed to the success of large-scale wind generation build-out in ERCOT, which include transmission access, an efficient energy market and ancillary services, and assessment of system frequency response performance.

Chapter 2: "Integration of Large-Scale Renewable Energy: Experience and Practice in China" focuses on the impact of integrating intermittent renewable energy on the security and stability of a power system. Through a recent event in which a large number of wind turbines were involved in serial trip-offs and went offline because of transient voltage problems; the lessons learned are summarized and three levels of defense in power system are described as countermeasures to enhance the stability of a power grid with a large amount of VERs.

Chapter 3: "The Role of Ensemble Forecasting in Integrating Renewables into Power Systems: From Theory to Real-Time Applications" presents a review of existing ensemble forecasting techniques to form a profound understanding of how ensemble forecasts is the key element to integrate VERs successfully into the power systems via increased reliability, early detection of risk, forecasting, and assistance in day-ahead and intraday balancing strategy.

Chapter 4: "Wind and Solar Forecasting" discusses other important aspects of wind and solar forecasting from the end user perspective. It introduces fundamental principles to guide how a forecasting solution should be optimized in order to provide maximum value to the end user. These principles consist of four components: sense, model, assess, and communicate. An in-depth description of the concept, significance, and connectivity of these four components in the context of wind/solar power forecast is provided.

Chapter 5: "Reserve Estimation in Renewable Integration Studies" analyzes the impacts of renewable energy on reserve requirements. It highlights and compares the methods for modeling required reserves, in addition to providing a description of the current policies for reserve provision.

Chapter 6: "Balancing Authority Cooperation Concepts to Reduce Variable Generation Integration Costs in the Western Interconnection: Consolidating Balancing Authorities and Sharing Balancing Reserves" explores the issues surrounding the consolidation of a larger operation area in order to maintain a better power balance. Through a case study of the Western Electricity Coordinating Council (WECC), the chapter demonstrates the benefits of a larger operation footprint through the savings in production cost and reduction in reserve requirements.

Chapter 7: “Robust Optimization in Electric Power Systems Operations” discusses one of the most important operations for independent system operators, unit commitment (UC), in the presence of VERs. Solving UC to optimality or near-optimality is crucial to reduce economic costs of operation, ensure a fair market outcome, and maintain a high security and reliability level in power systems. This chapter describes a robust optimization model which requires less accurate information on probability distributions of uncertain parameters, guarantees a higher level of feasibility (i.e., robustness) of the resulting solutions in the face of uncertainty, and leads to computationally more tractable and scalable models.

Chapter 8: “Planning of Large Scale Renewable Energy for Bulk Power Systems” introduces coordinated system planning to solve the reliability problem due to the high penetration of renewable power plants using asynchronous generators. This chapter specially discusses sub-synchronous resonance and voltage oscillations in addition to emerging techniques, such as parallel processing, that are used in these computation-intensive planning studies.

Chapter 9: “Voltage Control for Wind Power Integration Areas” describes the basic functions of a wind-automatic voltage control system (Wind-AVC) and its implementation to improve the grid’s stability and solve the problem of voltage fluctuations caused by the intermittent output of the wind turbine generators and the relatively weak grid structure.

Chapter 10: “Risk Averse Security Constrained Stochastic Congestion Management” presents an innovative probabilistic security constrained congestion management (PSCCM), considering the probable outage of main elements of power systems as well as the uncertainty of wind power generation. The proposed approach is formulated as a two-stage stochastic programming problem, in which both of the base case (first stage) and all probable severe post-contingency states (second stage) are considered together. The control actions performed on the base case operation point are called preventive controls, whereas those activated following the occurrence of contingencies are corrective controls.

The future of VERs is promising as they offer many benefits to the grid and society as a whole. While this book covers the topics associated with the integration of VERs as comprehensively as possible, more work is still under development. The intent of this book is not only to help to adapt to a future grid with the benefit of installed renewable energy capacity fully explored but also to encourage more people to contribute to this dynamic field and enable further exploitation of new revolutions for renewable integration.

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