Preface

In recent years, wind power and photovoltaics (PV) have experienced a rapid growth around the world. As representatives of renewable energy, large number of wind power and PV have been integrated into power systems because of their low-carbon superiority and continuously decreasing investment cost. Countries around the world set aggressive goals for high penetration of renewables in future power systems to decarbonize the energy system. Large scale centralized renewable generations are connected to transmission grids in countries such as China and United States. In some other countries, distributed renewables are employed to partially supply the load in distribution systems. According to the estimate of the *Energy Transition Outlook: Renewables, Power and Energy Use Report*, 85% of the world electricity will be supplied by renewable energy in 2050 (`http://www.ourenergypolicy.org/wp-content/uploads/2017/09/DNV-GL_-Energy-Transition-Outlook-2017_renewables_lowres-single_0109.pdf`).

The fast development of renewable energy continuously changes the behavior of the power system. Uncertainty and variability are the two most significant features of renewable energy. However, power systems have always been designed for controllable generators such as thermal and hydro-power generators instead of intermittent energy for more than a century. The uncertainty and variability of renewables will fundamentally change the way that the power system balances the generation and load, in terms of both planning for the long term and operation the short term, and in both transmission and distribution networks. The aim of many emerging power system technologies is exactly to increase the flexibility of the power system to accommodate more renewable energy. To face this ever-changing power system trend, new theories and methodologies for analytics and optimization are required for the planning and operation of the future power system.

Stochastic mathematics made great progress in recent decades. It not only helps us understand the uncertainties in our everyday life but also provides wisdom and skills to handle the uncertainty. More and more stochastic mathematics are starting to be used in power system analytics and decision making. It is evident that stochastic mathematics analytic and operation techniques will benefit the power system with renewable energy integration, in terms of both security and economy.

The scope of this book covers the modeling and forecasting of renewable energy as well as operation and planning of power systems with renewable energy integration. The book can be divided into four parts as shown in Figure 1. The first part presents some stochastic mathematics theories as a preparation for reading the main part of the book. The second part presents various modeling and analytic techniques for renewable energy generation, including how to model long- and short-term renewable energy uncertainty, what the dependencies among multiple renewable power plants will be, how to simulate renewable energy generation, and how to find representative output time series. The third part provides solutions of how to handle the uncertainty of renewable energy in power system operation, including a fast and efficient algorithm to calculate the probabilistic power flow, risk-based stochastic unit commitment models to acquire the optimal generation schedule under uncertainty, an efficient operation strategy for renewable power plants participating in electricity markets, and how to make the tie-line scheduling under uncertainty. From the perspective of long-term planning, the last part introduces a series of efficient approaches on how to simulate long-term power system operation, how to calculate the capacity credit of renewable energy, how to optimize the location, the capacity, and the sequence for renewable investments, and how to optimize the generation and transmission expansion planning of power systems with renewable energy integration.

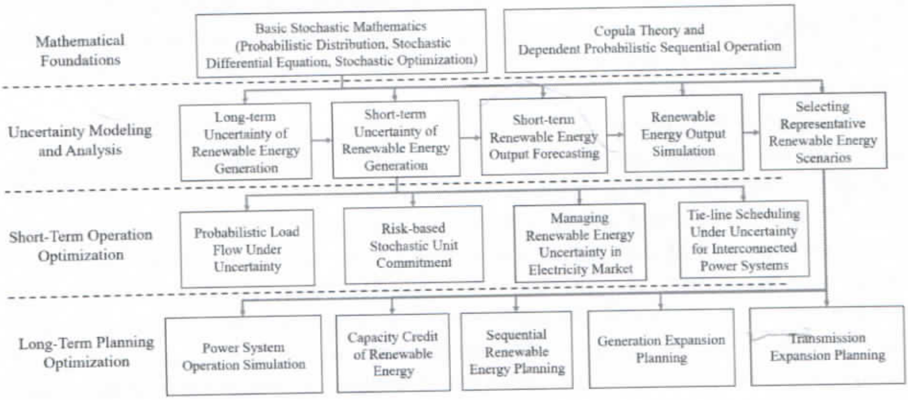

FIGURE 1 Research Framework of Analytics and Optimization for Renewable Energy Integration.

The aim of this book is threefold: **Firstly, the book provides a comprehensive understanding of the uncertain behavior of renewable energy generation.** For the power industry, the transition of deterministic thinking to stochastic is crucial for renewable energy integration. This book not only explains it from a theoretical prospective but also describes how to understand this problem from an engineering point of view. **Secondly, the book provides state-of-art mathematics and methodologies for power systems under uncertainty.** We think stochastic mathematics will play an important role in the future power system. Therefore this book proposes a whole range of models, from basic models to deal with the uncertainty, to small math skills to make the calculation tractable. It opens the door to develop practical decision-making tools for power system operation and planning with high renewable energy penetration. **Thirdly, this book helps the reader to understand the impact of renewable energy integration on power systems.** The book provides many case studies to demonstrate the cost of hedging against renewable energy uncertainty and the benefit of integrating renewable energy, how the renewable energy integration affects the decision-making process, and to what extent the power system economy, reliability, and environmental impact will be changed with renewable energy integration. Especially, some case studies use real-world data and provide some practical information and experiences from industry.

The content of this book is as follows:

Chapter 1 provides several fundamental stochastic mathematics techniques for uncertainty analysis and modeling including probability theory, stochastic differential equations, and the stochastic process and scenarios. These basic theories and techniques will be used in the analytic and optimization of renewable energy in this book.

Chapter 2 introduces the method to model and calculate multiple stochastic dependent variables using copula theory and dependent probabilistic sequence operation (DPSO). DPSO can be viewed as discrete convolution that is able to handle dependent variables. It has wide applications in power system reliability assessment, reserve quantification, probabilistic forecasting, etc.

Chapter 3 proposes the long-term uncertainty models for wind power and PV generation. We use the copula function to model the distribution of multiple wind farms or PV stations in order to capture their spatiotemporal dependencies. Their long-term fluctuation is modeled by autocorrelation functions. Compared with wind power, the output of PV shows obvious periodicity. We show how to divide the PV output into the deterministic part and stochastic part.

Chapter 4 addresses the issue of renewable energy forecasting. Considering the fact that the accuracy of short-term wind power forecast highly depends on numerical weather prediction (NWP), we propose an improved forecasting approach by mining the outliers of NWP, where outliers are detected by feature extraction and K-means clustering.

Chapter 5 proposes short-term uncertainty models for wind power and PV generation. The short-term uncertainty of renewable energy is reflected as the forecast error. We use the copula function to model the dependencies between the real output and its forecasted value among different renewable energy sites. The conditional forecast error of renewable energy can then be obtained, which provides the uncertainty of the wind power / PV forecast varying with the level of its output.

Chapter 6 introduces renewable energy operation simulation techniques. The need for such techniques is that there usually is not enough clean historical data to be used in power system long-term planning. We propose a sequenced differential equation-based method to simulate the wind speed and the shedding of solar radiation to further obtain long-term output of wind power and solar radiation. The proposed method is able to simulate massive renewable energy output data that retain the basic characteristics of wind power and PV output, including their intermittence, variety, and dependency.

Chapter 7 proposes the method of finding representative renewable energy scenarios. Several scenario reduction methods are proposed and are compared using several evaluation metrics. The obtained representative renewable energy scenarios act as the basis of the scenario-based stochastic optimization problems.

Chapter 8 conducts probabilistic load flow analysis with high penetrated renewable energy. It combines dependent probabilistic sequence operation and a novel linear power flow model to boost the computational efficiency. Since there are so many dependent uncertain injections in the networks, dependent probabilistic sequence operation suffers from the curse of dimensionality. An effective high-dimensional dependent probabilistic sequence operation calculation method is provided.

Chapter 9 proposes a risk-based stochastic unit commitment model to address the renewable energy uncertainty in short-term power system operations. The risks of the loss of load, renewable energy curtailment, and branch overflow caused by renewable energy uncertainty are analytically formulated in the unit commitment model. The model is proven to be able to be transformed into a mixed integer linear programing and shows efficiency improvements compared with the scenario-based unit commitment model.

Chapter 10 discusses the operation strategy of renewable energy producers participating in electricity markets. The renewable energy producer is allowed to participate in both energy and reserve markets to hedge the generation uncertainty. The optimal bidding strategy for renewable energy producers under probabilistic forecast to maximize their expected revenue in the market is analytically derived.

Chapter 11 addresses the issue of tie-line scheduling of inter-connected power systems with large-scale renewable energy integration. We propose an improved tie-line scheduling approach that is able to optimize the electricity exchange and share reserves among different balancing areas by considering the renewable energy integration quota in each area.

Chapter 12 introduces the power system operation simulation technique considering large-scale renewable energy integration. The operation simulation considers the operation characteristics of different kinds of generation such as renewable energy, coal / gas thermal power, hydro power, pumped hydro storage, nuclear power and combined heat and power generators. Detailed power system topology and the transmission capacity of AC/DC transmission lines are considered. Calculation acceleration techniques are proposed so that the model is able to carry out 8760-hour year-round operation simulation in a reasonable time. We provide several case studies using real-world data to demonstrate the application of this technique in thermal generation cost variation analysis due to renewable energy integration, wind power accommodation analysis, and pump storage planning.

Chapter 13 discusses the issue of capacity credit of renewable energy from both a numerical calculation prospective and analytical derivation. A dependent probabilistic sequence operation-based method is proposed that can quickly and accurately evaluate the capacity credit of renewable energy. An analytical model based on a reliability function is proposed that uncovers the factors that influence the value of the capacity credit.

Chapter 14 proposes a sequence and location planning method for renewable energy. The model optimizes the sequence and location of the wind farm to maximize the overall energy production and capacity value of wind power. The wind resource and the dependencies between different sites are considered. Since the optimization model is un-analytical, ordinal optimization theory is applied to identify suboptimal decisions.

Chapter 15 proposes a stochastic long-term generation planning model to efficiently integrate wind power. The uncertainty of wind power generation is represented by scenarios, including both typical and extreme scenarios. Since it is difficult to directly solve the proposed two-stage stochastic planning model considering multiple scenarios, an improved Benders decomposition algorithm is introduced to accelerate the model solving.

Chapter 16 proposes a stochastic long-term transmission planning model to efficiently integrate renewable energy. Both long-term and short-term uncertainties are considered in this model, which are described via scenarios and operating conditions, respectively.

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