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Security-constrained expansion planning of fast-response units for wind integration☆

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ABSTRACT

This paper proposes a stochastic expansion planning of fast-response thermal units for the large-scale integration of wind generation (WG). The paper assumes that the WG integration level is given and considers the short-term thermal constraints and the volatility of wind units in the planning of fast-response thermal units. The new fast-response units are proposed by market participants. The security-constrained expansion planning approach will be used by an ISO or a regulatory body to secure the optimal planning of the participants' proposed fast-response units with the WG integration. Random outages of generating units and transmission lines as well as hourly load and wind speed forecast errors are modeled in Monte Carlo scenarios. The Monte Carlo simplification methods are introduced to handle large-scale stochastic expansion planning as a tradeoff between the solution accuracy and the calculation time. The effectiveness of the proposed approach is demonstrated through numerical simulations.

1. Introduction

The increasing socio-environmental concerns have persuaded governments to support large integrations of renewable generation in power systems by introducing mandatory Renewable Portfolio Standards (RPS) or equivalent policies [1]. The large integration of intermittent wind generation (WG) in power systems has necessitated the inclusion of more innovative and sophisticated approaches in power system operation and planning [2].

In this paper, the intermittency refers to a situation where the power output of WG is less than a minimum amount over an extended time. While the volatility points out to smaller WG fluctuations in a shorter time. A major challenge in power systems is to determine the optimal availability of reserves to compensate WG uncertainties. Without a sufficient supply of reserves, the power system may not be able to provide short-term ramping support to contain large WG variability. However, the real-time allocation of a large sum of reserves may not be feasible when considering the economics and the security of power systems. Here, the allocation of excessive thermal reserves could further increase the operating costs while thermal reserves supplied by remote generating units may not be readily accessible due to transmission constraints.

The deterministic allocation of thermal reserves (e.g., largest generation unit in the system or certain percentages of load and WG) may offer a sub-optimal solution. Large integrations of intermittent WG could further contribute to the vulnerability of power systems [3–5]. Hence, it is necessary to apply stochastic optimization methods to address major WG integration concerns such as the coordinated expansion of WG and fast-response generation units, uncertain nature of systems with WG units, and short-term operating constraints of power systems.

The operation planning of WG integration is proposed in Ref. [6]. The reliability of composite generation and transmission system with a large-scale WG integration is investigated in Ref. [7]. The Monte Carlo simulation is used in Ref. [8] to investigate the effect of wind and load forecast errors on the power system expansion planning.

However, only a few studies in the literature considered the complicated operation issues in the WG expansion planning problem. The problem in Ref. [9] provides a nonlinear wind-thermal model and applies the evolutionary programming to large-scale power systems. A coordinated wind-thermal dispatch is presented in Ref. [10] by applying the direct search method to the WG integration. A combination of branch and bound and dynamic programming is considered in Ref. [11] for a coordinated economic dispatch of wind and thermal units in isolated power systems. The impact of transmission lines on the WG expansion is discussed in Ref. [12]. The approach considers additional zonal reserves because of the WG uncertainty. The incorporation of the WG model in the optimal economic dispatch is discussed in Ref. [13]. The study in Ref. [14] considers the short-term operation along with the long-term

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planning, where renewable energy resources are operated along with conventional generating systems to satisfy certain objectives. A comprehensive study of the operation of power systems when considering the WG integration is presented in Ref. [15]. The study shows that, at the present time, frequency control is not a significant challenge when integrating WG into large power systems. However, such issues will become more of a challenge for systems with large penetrations of WG. Recently, North American Electric Reliability Corporation (NERC) released a report on the planning and the operation of power systems with large sums of WG [16].

This paper proposes a stochastic expansion planning of fast-response thermal units for the large-scale integration of WG. The level of WG integration is assumed to be given. The site and the year of installation of fast-response units are proposed by the participants. The ISO does not plan any generating units. Rather the ISO would acknowledge and optimize the proposed planning of fast-response units that would provide both the reserve capacity and the fast ramping required for large WG integrations. The fast-response units in the paper assumed to have the ability to reach their maximum capacity in a short period. The inclusion of the hourly unit commitment is essential when considering the WG variations and ramping constraints. The paper considers the short-term thermal constraints and the volatility of wind units in the planning model and applies a decomposition model for utilizing the hourly unit commitment states. Random outages of generating units and transmission lines as well as load and wind speed forecast errors are modeled in scenarios using the Monte Carlo simulation. The Monte Carlo simplification methods are introduced to handle large-scale the stochastic expansion planning as a tradeoff between accuracy and calculation time. The proposed stochastic generation expansion planning approach would inherently form a large-scale optimization problem and a decomposition method is used to alleviate the calculation burdens. The application of mixed-integer programming (MIP) presents attractive features including a fast convergence, simplicity of the model, linearity of constraints, and the ability to handle large-scale problems [17]. The approach can be used by an ISO or a regulatory body to secure the optimal planning of fast-response units proposed by market participants while considering the large-scale WG integration. The contribution of the paper is to consider and utilize new fast-response generating units in power systems that would accommodate large WG integrations. The impact of WG dispersion (i.e., centralized or distributed) on the power system operation and planning is investigated. The planning problem, when considering the WG uncertainty, would present a large-scale problem with major computation burdens. Several improvements in decomposition and modeling are considered in this paper to make the proposed approach more practical.

Other alternatives such as the demand response and the application of storage systems may accommodate the WG uncertainty. However, such alternatives are usually available in small quantities as compared with large WG variations in power systems [18,19]. The application of responsive demands may incur additional investments on communication facilities between the supply and the demand [20].

The rest of this paper is organized as follows. Section 2 describes the modeling of uncertainties in the proposed model. Section 3 presents the framework and the decomposition procedure applied to the model. Section 4 provides a detailed formulation of the problem and the solution methodology. Section 5 presents and discusses the case studies for a six-bus system and the IEEE 118-bus system over a 10-year planning period. The conclusions drawn from the case studies are provided in Section 6.

2. Uncertainty in power system planning

The uncertainty can be categorized into (1) the participant level uncertainty which includes fuel availability and emission costs, discount rates, investment costs, competition, etc., and (2) the ISO level uncertainty which includes random component outages and load and wind forecast errors. The financial risks are usually included in the market participant portfolio optimization [21]. As this paper assumes that the investors have already submitted their expansion planning proposals to the ISO, the participant level uncertainty is not considered. Accordingly, the ISO's uncertainty is considered in scenarios to maintain the reliability index at an acceptable level. The ISO assumes the stochastic behavior of power systems corresponding to component outages and load and wind forecast errors by deploying an optimal level of generation reserves. The embedded expansion planning risk, assumed to be undertaken by the ISO, is modeled in Section 4 by adding the cost of imaginary units to the ISO's objective function.

The Monte Carlo (MC) simulation method is adopted to simulate random characteristics of power systems. The proposed stochastic planning model would consider multiple scenarios in the Monte Carlo simulation [23,24]. To address the uncertainty of WG, we assume the wind power is subject to a Weibull distribution. The detailed modeling of WG uncertainty with a Weibull distribution is provided in Refs. [13,22]. The Monte Carlo simulation will generate a large number of scenarios considering wind speed forecast errors. In each scenario, the hourly WG is considered to be given.

To consider random outages of generators and transmission lines, we use UX and UY vectors in the Monte Carlo simulation, which $UX_{iht} = 1$ indicates that the *i*th generator is available in year *t* and scheduling period *h* while $UX_{iht} = 0$ indicates otherwise. Likewise, $UY_{jht} = 1$ indicates that the *j*th transmission line is available in year *t* and scheduling period *h* while $UY_{jht} = 0$ indicates otherwise [23].

To consider load forecast errors, the annual peak load forecast is expressed as the base load times the annual growth rate. The annual growth rate consists of an average growth rate and a random component. Normally distributed random components are assumed to be added to the average growth rates in order to reflect an uncertain economic growth or weather changes in the load forecast [24]. The hourly load at each bus is then determined based on the annual system peak load using given load distribution factors.

Each scenario is assigned a probability of occurrence, PRs, that is one divided by the number of generated scenarios. The number of scenarios has a substantial impact on the computational requirements for solving scenario-based optimization models. Therefore, using an effective scenario reduction method could be very essential for solving large-scale systems [25]. The reduction technique is a scenario-based approximation with a smaller number of scenarios and a reasonably good approximation of original system. Therefore, we determine a subset of scenarios and a probability measure based on the subset that is the closest to the initial probability distribution in terms of probability metrics. The General Algebraic Modeling System (GAMS) is used in this study. GAMS provides a tool called SCENRED for scenario reduction and modeling random data processes. These scenario reduction algorithms provided by SCENRED determine a scenario subset (of prescribed cardinality or accuracy) and assign optimal probabilities to the preserved scenarios [26].

3. Planning model description

Fig. 1 depicts the proposed planning model. The Benders decomposition is used to decompose the planning problem into the optimal investment plan as master problem, and