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Optimal capacity and type planning of generating units in a bundled wind–thermal generation system

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HIGHLIGHTS

- A bundled wind–thermal generation system (BWTGS) planning model is presented.
- Operational characteristics of units and constraints of system are considered.
- Techniques to accelerate the computation are developed.
- Optimal type and number of thermal units for constituting a BWTGS can be determined.
- Impacts of transmission power on planning results are analyzed.

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ABSTRACT

Integration of large-scale wind power creates challenges for power system operations. One of the effective ways of dealing with these challenges is to build thermal power plants to form bundled wind–thermal generation system (BWTGS), i.e., using thermal power to alleviate the fluctuation of wind power. This paper presents a method for optimal capacity and type planning of BWTGS with the given wind farms. Branch-descending technique (BDT) is used to generate candidate schemes of thermal generating units by analyzing the rules of total cost changing with the reduction of the number of thermal generating units. The optimal scheme of BWTGS can be obtained by simulating a long-term operation process of BWTGS and comparing the total costs of all schemes. Techniques to accelerate computation, such as combining redundant states in dynamic programming (DP) algorithm and the saving-branch-cost technique in BDT, are developed to reduce the computational complexity. The major advantage of the proposed method is that it can be used to obtain not only the optimal capacity of thermal generating units, but also the optimal type and number of thermal generating units. Case studies are conducted to demonstrate the effectiveness of this proposed method.

1. Introduction

Wind energy is considered as a promising renewable energy resource due to its extensive availability, no fossil fuel consumption and zero greenhouse gas emissions. Recently, the exploration and utilization of wind energy have seen rapidly developed around the world. In China, more than twenty large-scale wind farms, each of which has an installed capacity about 1GW, have been designed and are being constructed since 2011 [1]. The utilization of these wind farms will be helpful in reducing the fossil fuel consumption and greenhouse gas emissions. However, the integration of large-scale volatile wind power also creates great challenges for power system operations and may even lead the system to non-dispatchable situations [2,3].

In China, these planned large-scale wind farms are usually near the areas with abundant coal reserves. Therefore, one of the feasible plans of utilizing the large-scale wind power is to build coal-fired power plants close to these wind farms and form bundled wind–thermal generation systems (BWTGSs). In this manner, the BWTGSs can be used to transmit the combined wind–thermal power to the heavy load centers in the southeast of China and alleviate the operation burdens of connected power systems. The schematic map of developing BWTGSs is shown in Fig. 1.

In general, research regarding the coordination of wind–thermal generation systems can be categorized into two areas: the coordinated operation research (namely the wind–thermal unit

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Nomenclature

- A, B, C Constants in wind power model
- ASR_{down}/ASR_{up} Additional down/up spinning reserve requirement due to wind power penetration
- a_i, b_i, c_i Coefficients of the quadratic production cost function of thermal generating unit i
- $BSR(t)$ Basic spinning reserve requirement without considering wind power penetration.
- CC_k Capital cost of scheme k
- $C_{total,k}$ Total cost of scheme k
- $C_{total,opt}$ Total cost of the optimal scheme of BWTGS at a given basic transmission power
- CSU_i/HSU_i Cold/hot startup cost of generating unit i
- $DS_i^{\max}/US_i^{\max}$ Maximum down/up spinning reserve contribution of generating unit i
- $DS_i(t)/US_i(t)$ Down/up spinning reserve contribution of generating unit i at hour t
- $DR_i^{\max}/UR_i^{\max}$ Maximum ramp-down/ramp-up rate of generating unit i
- $D(t)$ Expended change of total power output of generating units between hour t and hour $t+1$
- $D_{\max}(t, W)$ Maximum change of total power output of generating units from hour t to hour $t+W$
- $F_i(\cdot)$ Production cost function of generating unit i
- F_{oc} Operation cost in T hours
- $F_{oc,j,k}$ Operation cost of scheme k in the jth year
- IS Initial status of generating units
- M Planning period
- N Number of generating units
- NT Number of trees in BDT
- P_{BT} Basic transmission power
- $P_D(t)$ Change of total power output of generating units between hour t and hour $t+1$
- $P_i(t)$ Power output of generating unit i at hour t
- $P_i^{\max}(t)/P_i^{\min}(t)$ Maximum/minimum power output of generating unit i at hour t
- $P_{i,r}^{\max}/P_{i,r}^{\min}$ Maximum/minimum rated power output of generating unit i
- $P_T(t)$ Transmission power at hour t
- $P_w(t)$ Power output of wind turbine generator (WTG) at hour t
- $P_{w,avg}$ Average power output of WTGs in T hours
- $P_{w,r}$ Rated capacity of WTG
- $P_{w,total}(t)$ Total power output of WTGs at hour t
- r Discount rate
- r_{coal} Increasing rate of coal price
- $S(t)/S_{add}(t)$ Number of strategies/additional strategies saved at hour t in DP algorithm
- S_{basic} Number of basic strategies in DP algorithm
- $SD_i(t)/SU_i(t)$ Shutdown/startup cost of generating unit i at hour t
- $SR_i^{\max}$ Maximum startup ramp rate of generating unit i
- T Hours in a year ($T = 8760$)
- T_i^{cold} Cold start hours of generating unit i
- T_i^{minoff}/T_i^{minon} Minimum off/on time of generating unit i
- $T_i^{off}(t)/T_i^{on}(t)$ Time period that generating unit i has been continuously off/on till hour t
- $U_i(t)$ State of generating unit i at hour t (1: on, 0: off)
- VS Valid set of schemes
- $v(t)$ Wind speed at hour t
- v_{ci}, v_{co}, v_r Cut-in, cut-out and rated wind speed
- W Leading hours of various strategies in DP algorithm
- $\alpha\%$ Coefficient of basic spinning reserve requirement
- $\beta\%$ Coefficient of additional up/down spinning reserve requirement
- $\gamma\%$ Percentage of spinning reserve contribution of generating units
- $\delta\%$ Range of transmission power
- ρ Expansion coefficient of various strategies in DP algorithm

commitment (UC) problem) [4–14] and the coordinated planning research (namely the wind–thermal generation expansion planning problem) [15–24].

Many methods have been developed for the wind–thermal UC problem. A simulation method on the wind power penetration was proposed to reduce the system operation costs and greenhouse gas emissions [4]. Moreover, studies from the perspective of wind forecasting uncertainty on the operation cost and spinning reserve requirement have been reported [5,6]. The incorporation of sub-hourly resolutions, which will impact the operation cost of the system, to the wind–thermal UC problem has been developed [7,8]. In [9,10], stochastic UC models considering the demand and wind generation uncertainties were proposed. Their results show that the adoption of stochastic UC model is superior to the deterministic model in terms of reducing both the operation cost and the scheduling risk of power systems. In [11], the UC model was formulated as a three-stage optimization problem and the objective of the model was to maximize social welfare under worst-case wind power output and demand response scenarios. Different from [11], Álvarez-Miranda et al. [12] divided the UC model into two stages. In the first stage, a bootstrap predictive inference approach was adopted to generate the forecast of wind power, and then the UC was executed using the output from the first stage. Zhang et al. [13] utilized the operational cost plus the greenhouse gas emission cost as the objective function of the wind–thermal UC model. A hybrid algorithm based on the sequential quadratic programming and particle swarm optimization was employed to solve the model. Ji et al. [14] employed the quantum-inspired binary gravitational search algorithm to solve the thermal-wind UC problem. Techniques such as the start-up priority list and mutation adjustment strategy were developed to accelerate the searching process and to prevent the premature convergence.

For the generation expansion planning problem, models considering the wind power penetration and the incorporation of reliability/security constraints were proposed in [15,16], and multi-objective models were formulated in [17,18]. Rather than planning conventional generating units, the research of [19–21] focuses on the planning of wind farms in the power systems. A bi-level stochastic optimization model, which considers the equipment failures, the uncertainty of wind speed, and the variability of the demand throughout the planning period, was proposed to handle the generation expansion planning problem in [22]. In [23], a long-term optimal energy mix planning method was presented to achieve the coordinated planning of different energy resources (coal, wind and solar, etc.). Billinton and Karki [24] developed a reliability/cost evaluation model to determine the optimum capacity expansion plan in a small power system. In their work, various schemes consisting of different installed times, types and penetration levels of wind power, PV and diesel were compared.

In addition to the aforementioned two main research areas, a number of literatures [25–30] link the wind–thermal coordinated operation and the wind–thermal coordinated planning together. Either the generation expansion planning problem contains the