

Research on Operation Strategy for Bundled Wind-thermal Generation Power Systems Based on Two-Stage Optimization Model

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Abstract. Wind power has the advantages of being clean and non-polluting and the development of bundled wind-thermal generation power systems (BWTGSs) is one of the important means to improve wind power accommodation rate and implement "clean alternative" on generation side. A two-stage optimization strategy for BWTGSs considering wind speed forecasting results and load characteristics is proposed. By taking short-term wind speed forecasting results of generation side and load characteristics of demand side into account, a two-stage optimization model for BWTGSs is formulated. By using the environmental benefit index of BWTGSs as the objective function, supply-demand balance and generator operation as the constraints, the first-stage optimization model is developed with the chance-constrained programming theory. By using the operation cost for BWTGSs as the objective function, the second-stage optimization model is developed with the greedy algorithm. The improved PSO algorithm is employed to solve the model and numerical test verifies the effectiveness of the proposed strategy.

1. Introduction

The slather of traditional fossil energy resources brings us lots of austere environment and social problems. Compared with the fossil energy, wind energy has the characteristics of being abundant, clean and non-polluting. To improve wind power accommodation ratio is of great significance to alleviate the energy shortage and improve the environment. Wind power has uncontrolled characteristics of randomness, volatility and intermittence, which make wind power integration have adverse effects on power system, such as the optimization of reactive power[1], active power dispatching[2][3]etc..

The BWTGSs is one of the important means to improve wind power accommodation rate. Many scholars have carried on related researches on the BWTGSs. By taking the wind speed of wind farm and the load characteristics of the receiving power system into account, a sectionalized and range-fluctuated power transmission model is formulated in [4]. The research in [5] proposes a scheme replacing conventional reactive power compensation device with SVC. By analyzing the variation of the total cost with number of thermal power units, the optimal capacity and type of thermal power



units are put forward in [6]. To deal with optimal configuration of wind & coal combined transmission, capacity allocation and high voltage DC location with the constraints of power system security and peak load regulating capacity, a comprehensively optimal objective function was established in [7].

Based on above researches, two-stage optimization model is formulated with chance constrained programming theory. The first-stage optimization model is taking environmental benefit as objective function and supply-demand balance and generator operation as constraints. It is easy to sacrifice too much operation cost to guarantee the best environmental benefit index in the first-stage optimization. The second-stage optimization is taking operation cost of BWTGSs as objective function. At last, numerical test verifies the effectiveness of the proposed strategy.

2. The model of BWTGSs and load characteristics

2.1. The model of the thermal power plant

Thermal power plants are usually equipped with multi thermal power units, and the model of thermal power plants can be described by cubic polynomial[8]:

$$P_{thermal}(t) = \lambda_t \sum_i^n a_{1,i} + a_{2,i} P_G(i) + a_{3,i} P_G(i)^2 + a_{4,i} P_G(i)^3 \quad (1)$$

Where, λ_t is the simultaneous rate at t moment; n is the number of thermal power units.

2.2. The model of wind farm

To simplify the problem, a linear piecewise function is used to describe the output power of a single wind power generator[9].

$$P_W(t) = \begin{cases} 0 & v(t) < v_{in} \text{ or } v(t) > v_{out} \\ P_{W,r} \frac{v(t) - v_{in}}{v_r - v_{in}} & v_{in} \leq v(t) < v_r \\ P_{W,r} & v_r \leq v(t) \leq v_{out} \end{cases} \quad (2)$$

Where, $P_{W,r}$ is the rated output power of wind generator; v_{in} , v_{out} , v_r are cut-in wind speed, cut-out wind speed and rated wind speed, respectively; $v(t)$ is wind speed at t moment.

The output power of wind farm is related to the wind speed, number of wind generators, simultaneous rate etc. Suppose each wind generator is the same and the output power of wind farm is:

$$P_{Wind}(t) = \alpha_w \times \mu(t) \times N_w \times P_W(t) \quad (3)$$

Where, α_w is the influence coefficient, introduced wind wake effect; $\mu(t)$ is simultaneous rate of wind generators at t moment; N_w is the number of wind generators.

2.3. Load characteristics of receiving power system

Load characteristics of receiving power system is affected by weather, human, economic and other uncertain impacts. The load forecast can be decomposed into base load and random load, and base load is obtained from forecast results; random load is corresponding to load forecast error, and normal distribution is used to describe load forecast error. Probability density function of load forecast error[10]:

$$f_{\Delta P_L}(\Delta p_L) = \frac{1}{\sqrt{2\pi}\sigma_L} \exp(-\Delta p_L^2 / 2\sigma_L^2) \quad (4)$$

Where, ΔP_L is the load forecasting error random component; Δp_L is the load forecasting error; σ_L is a standard deviation of load forecasting errors.

So, load forecasting results of receiving power system is as follow:

$$P = P_L + \Delta P_L \quad (5)$$

Where, P_L is the base load.

3. Two-stage optimization model of BWTGSs

3.1. The first-stage optimization model

3.1.1. *Objective function.* The traditional thermal power plants use coal as fuel and produce a large number of pollutants. The pollution problem caused by the pollutants has a serious impact on the ecological environment and has restricted the development of social economy; Wind power is the most mature and efficient renewable energy, but the volatility makes wind power integration have some adverse effects on the power system. The BWTGSs can use the controlled thermal power unit to stabilize the volatility of wind power, so as to improve the wind power accommodation rate and reduce the adverse impact of wind power integration. The wind is a clean energy, the ratio of wind output power of BWTGSs is as the environment benefit index, and the maximization of the environmental benefit index is as the objective function for the first-stage optimization model.

$$F_1 = \sum_{t=1}^{24} \max \frac{P_{Wind}(t)}{P_{Wind}(t) + P_{thermal}(t)} \quad (6)$$

Where, $P_{Wind}(t)$ is output power of wind farm at t moment ; $P_{thermal}(t)$ is output power of thermal power plant at t moment.

3.1.2. *Constraints.* The constraints that the first-stage optimization model should meet are as follows:

1)The supply and demand balance constraint

$$P_{Wind}(t) + P_{thermal}(t) = P_L(t), t \in T \quad (7)$$

Where, $P_L(t)$ is the load of receiving power system at t moment; $T = \{1, 2, \dots, 24\}$.

2)Wind power generator output power constraint

$$\text{prob}\{P_{W,\min} \leq P_W(t) \leq P_{W,\max}\} \geq \beta_1, t \in T \quad (8)$$

Where, $P_{W,\min}$ and $P_{W,\max}$ is minimum and maximum output power constraints of wind power generator, respectively; β_1 is the given confidence level.

3)Thermal power unit output power constraint

$$\text{prob}\{P_{thermal,\min} \leq P_{thermal}(t) \leq P_{thermal,\max}\} \geq \beta_2, t \in T \quad (9)$$

Where, $P_{thermal,\min}$ and $P_{thermal,\max}$ is minimum and maximum output power constraints of thermal power unit, respectively; β_2 is the given confidence level.

4)Wind power compensation capacity constraint

$$\text{prob}\{P_{thermal,c} \geq P_{W,c}\} \geq \beta_3 \quad (10)$$

Where, $P_{thermal,c}$ is the compensation capacity per minute of thermal power unit; $P_{W,c}$ is variation per minute of wind power generator; β_3 is the given confidence level.

5)Power climbing constraint

$$\text{prob}\{P_W(t) - P_W(t-1) \leq \Delta P_{W,\max}\} \geq \beta_4 \quad (11)$$

$$\text{prob}\{P_{thermal}(t) - P_{thermal}(t-1) \leq \Delta P_{thermal,\max}\} \geq \beta_5 \quad (12)$$

Where, $\Delta P_{W,\max}$ and $\Delta P_{thermal,\max}$ are upper limit of wind generators and thermal generators, respectively. β_4 and β_5 are the given confidence level.

3.2. The second-stage optimization model

3.2.1. *Objective function.* The economic index refers to the minimum of BWTGSs operation cost in the premise of meeting the load of receiving power system. The results of the first-stage optimization model tend to use more cost to make the environmental benefit optimal, and it is difficult for operators

of BWTGSs to accept. To solve the problem, the second-stage optimization model based on greedy algorithm is proposed in this paper. In order to save the operation cost of a day, the operation cost of each period should be minimum. To lower the impact on environmental benefit of BWTGSs, the optimal result of the first-stage optimization model is taken as the constraint. The economic optimization goal of BWTGSs is as shown in (13).

$$F_2 = \sum_{t=1}^{24} \{\min(\gamma_1 P_{Wind}(t)\Delta t + \gamma_2 P_{thermal}(t)\Delta t)\} \quad (13)$$

Where, γ_1 is the unit cost of wind farm. γ_2 is the unit cost of thermal power plant.

3.2.2. Constraints. To ensure the satisfactory result of the first-stage optimization model, the constraint is as shown in (14).

$$\sum_{t=1}^{24} \frac{P_{Wind}(t)}{P_{Wind}(t) + P_{thermal}(t)} = F_1^* \quad (14)$$

Where, F_1^* is the optimal environmental benefit index of the first-stage optimization model.

Other constraints of the second-stage optimization model are as shown in (7) - (12).

4. Case study

4.1. simulation parameters settings

The effectiveness of proposed method is verified by the basic data of a regional power grid. The region's power grid daily load curve is as shown in Figure 1(the biggest load is 1200 MW; the minimum load is 900 MW). The load needs BWTGSs to provide, excluding other power plants output power.

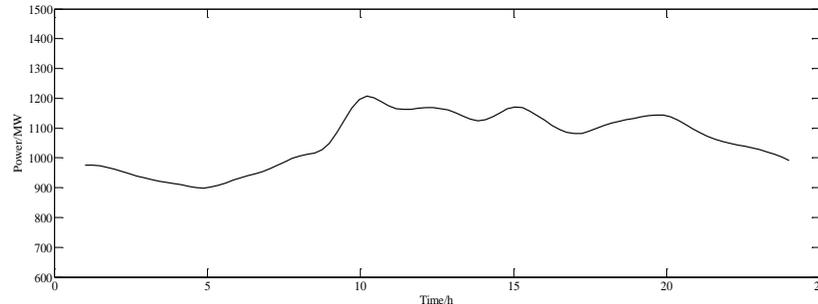


Figure 1. Daily load forecasting curve of a regional power grid

The wind farm capacity is 800MW and the rated capacity of the installed wind generator is 2MW. The cut-in wind speed, cut-out wind speed and rated wind speed are 3.33m/s, 15.28m/s, 8.33m/s, respectively. Considering the randomness of wind speed and wind direction, the influence coefficient of wind wake effect is taken as the random number, which follows the normal distribution. The thermal power plant is equipped with two 600 MW units and the minimum of the unit is taken as 30% of the rated capacity. The average cost of wind power and thermal power units are 0.56 yuan/ $kW \cdot h$ and 0.36 yuan/ $kW \cdot h$ [11], respectively. The confidence levels of all the constraints are taken as 0.9. The output power forecast of wind farm is as shown in Figure 2.

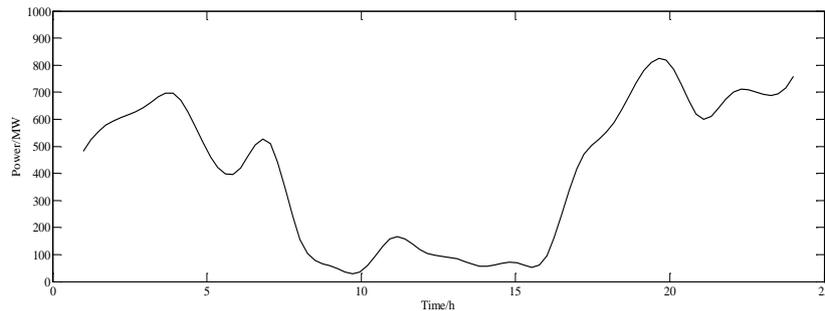


Figure 2. The power forecast result of someday

4.2. Result analysis

The improved PSO algorithm is employed to solve the mode. Considering the randomness of the PSO algorithm, the average result of 10 times is as the final result. In order to illustrate the advantages of two-stage optimization strategy, there are three modes offered in this paper: ① only the first-stage optimization; ② only the second-stage optimization; ③ two-stage optimization.

According to the model and solving process proposed in this paper, the results of different operation modes are as shown in Table 1.

Table 1. The results of different operation modes

Operation mode	Daily average environmental benefit (The ideal value is 0.4063)	Daily operation cost (million yuan)
① only the first-stage optimization	0.3765	1097.82
② only the second-stage optimization	0.1220	973.12
③ two-stage optimization	0.3511	1085.35

It can be known from Table 1 that according to the definition of the environment benefit index of this paper, when only the first-stage optimization, wind power accommodation rate is the highest and environmental friendliness of BWTGSs is the best, but its operation cost is the highest. So, mode ① uses the highest operating costs in exchange for the best environmental benefits, and its economic effect is not very good. When only the second-stage optimization, the economic effect of BWTGSs is the best, but its environmental benefit index is poor. Therefore, mode ② does not meet the requirement of “clean alternative” on the generation side. Two-stage optimization considers not only the operation economic index but also the environmental benefit index of BWTGSs. As a result, mode ③ reduces the operation cost of BWTGSs at the same time of ensuring the satisfactory environmental benefit index.

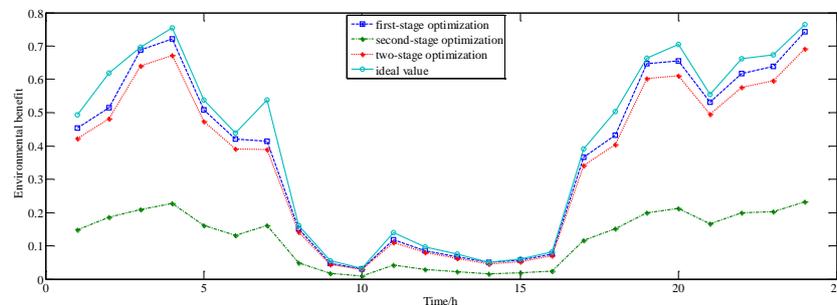


Figure 3. Daily environmental benefit index curves

Daily environmental benefit index curves of 3 operation modes are as shown in Figure 3. The ideal value of environmental benefit index can be obtained when the output power forecast of wind farm is accommodated by power system completely and is as the reference value of 3 operation modes. It can be known from Figure 4 that the environmental benefit index is very close to the ideal value, but is not

equal to the ideal value all the time. This is because there is wind speed forecasting error, and the margin of wind farm output power should be considered when setting up the operation strategy.

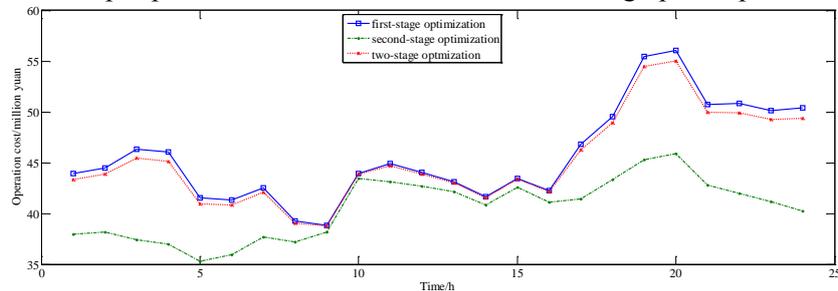


Figure 4. Daily operation cost curves

It can be known from Figure 3 and Figure 4 that the two-stage optimization strategy of BWTGSs considers the environmental benefit index and operation cost index comprehensively, which make the environmental benefit and operation cost located at the intermediate position of two single-stage optimization and the environmental benefit index is very close to the first-stage optimization result. This is because under the background of serious environmental problems and the implementation of “clean alternative” on the generation side, the optimization results of this paper is more emphasis on the environmental benefit index and reduces the operation cost of BWTGSs in the premise of ensuring the satisfactory environmental benefit.

5. Conclusion

In view of optimization operation of BWTGSs, two-stage optimization model is proposed considering wind speed forecast error and load characteristics of receiving power system using chance constrained programming theory. By comparing the simulation results of 3 kinds of optimization operation modes, economic index is ignored in only the first-stage optimization and the environmental benefit index is ignored in only the second-stage optimization. The two-stage optimization strategy of BWTGSs considers the environmental benefit index and operation cost index comprehensively. Under the background of increasingly serious environmental problems and the implementation of “clean alternative” on the generation side, the optimization results of this paper is more emphasis on the environmental benefit index and reduce the operation cost of BWTGSs in the premise of ensuring the satisfactory environmental benefit.

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References

- [1] YANG Junyou, CUI Jia, XING Zuoxia, et al. Reactive power control strategy for dispersed wind farm considering wind power forecasting [J]. *Automation of Electric Power Systems*, 2015 (13): 8-15.
- [2] LU Wentian, LIN Shunjiang, LIU Mingbo, et al. A Regional and Provincial Grid Coordination Optimization Method for Active Power Dispatch in AC/DC Interconnected Power System with Wind Power Integration [J]. *Automation of Electric Power Systems*, 2015 (7): 89-96.
- [3] Xie K, Dong J, Tai H M, et al. Optimal planning of HVDC-based bundled wind-thermal generation and transmission system[J]. *Energy Conversion & Management*, 2016, 115:71-79.
- [4] DONG Jizhe, XIE Kaigui, MA Chong, et al. Optimal Planning of Bundled Wind - thermal Generation Power Systems Con-sidering Wind Speed and Load Characteristics[J]. *Automation of Electric Power Systems*, 2016, 40 (15): 59-66.
- [5] ZHAO Yunhao, XIA Yi, ZHOU Qinyong, et al. Coordinated Control Strategy and

- Configuration Scheme of RPCD of DC System for Wind-Thermal-Bundled Power Transmission[J]. *Power System Technology*, 2016, 40 (7): 2081-2086.
- [6] Xie K, Dong J, Singh C, et al. Optimal capacity and type planning of generating units in a bundled wind-thermal generation system[J]. *Applied Energy*, 2016, 164:200-210.
- [7] WANG Zhidong, LIU Lianguang, LIU Zifa, et al. Optimal Configuration of Wind & Coal Power Capacity and DC Placement Based on Quantum PSO Algorithm[J]. *Proceedings of the CSEE*, 2014, 34 (13): 2055-2062.
- [8] ZHANG Wei. Research on Generating Characteristics Model for Thermal Power Plants [J]. *Journal of electric power*, 2002, 17 (1): 11-13.
- [9] ROY S. Market constrained optimal planning for wind energy conversion systems over multiple installation sites [J]. *IEEE Transactions on Energy Conversion*, 2002,17(1): 124-129.
- [10] YANG Jiaran , WANG Xingcheng, JIANG Cheng, et al. Multi-objective dynamic optimal scheduling of power system considering wind power risk [J]. *Power System Protection and Control*, 2016, 44 (7): 25-31.
- [11] YU Kun, CAO Yijia, NI Yixin, et al. Review of research on distributed generation technology and its integrated operation [J]. *Journal of Hohai University(Natural Sciences)*, 2009, 37 (6): 741-748.