A Transmission System Planning Method Considering Demand-side Response and Capability for Accommodating Wind Power

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Abstract. The large-scale development of grid-connected wind power, which is intermittent, random and uncontrollable, has introduced great challenges to power system planning and operation. Power system planning should fully consider the capability for accommodating wind power, as well as system's regulation capability and spare capacity. Given this background, a bi-level transmission system planning model for this purpose is proposed in this paper. In the proposed model, demand-side response resources, such as incentive load and interruptible load, are used for peak-load shifting so as to optimize power flow distribution, reduce transmission investment and improve the utilization level of wind power. The two levels are implemented interactively and iteratively, and finally converge to an optimized planning scheme considering both security and economy. The essential features of the developed model and adopted algorithms are demonstrated by a modified 18-bus test system.

1. Introduction

These With the increasing exhaustion of fossil energy, many countries have developed clean energy such as wind power and photovoltaics in recent years[1]. The intermittent, random and uncontrollable nature of wind power has resulted in new problems and challenges to the secure and economic operation of the power system concerned. On the one hand, the capability for accommodating wind power should be considered for the outstanding phenomenon of wind curtailment. On the other hand, higher requirement is imposed on system's regulation capability and spare capacity, and thus additional spare capacity are needed to cope with the random fluctuation of wind power and maintain power balance and power system stability.

As for the planning of transmission systems with wind farms, some research has been conducted at home and abroad. In [2], a transmission planning model of the wind-storage joint system is established with the goal of maximizing the total benefit of the system. The authors in [3] combine two planning problems into a single planning problem and numerically show the benefits of their combination. In [4], a transmission planning approach considering correlation of wind power is proposed. The spatial dependence of neighboring wind farm outputs is modeled by Copula theory. A BGTEP model is proposed in [5] and the optimal planning for along-term period is obtained such that the cost of
installation and operation would be minimized. In [6], a novel generation and transmission expansion planning model considering positive and negative climbing ability of conventional units and N-1 security constraints is proposed. In [7], a multi-objective integrated generation and transmission expansion planning taking into account the uncertain load and wind power production with one objective function is proposed. In [8], a transmission network planning model which considers the influence of the wind-storage system is established. Generally speaking, existing research on transmission system planning with wind power is relatively preliminary. The development of demand-side response resources, however, provides a new measures to cope with the uncertain output of wind power and improve the capability for accommodating wind power.

Given this background, a bi-level transmission system planning model considering demand-side response and capability for accommodating wind power is proposed. Demand-side management and wind power abandonment are regarded as reserve resources. Finally, the essential features of the developed model and adopted algorithms are demonstrated by a modified 18-bus test system.

2. Transmission System Planning with Wind Farms
Traditionally, transmission system planning is to seek a planning scheme that can minimize investment costs and operating costs while ensuring the reliability of the power system concerned.

As the penetration of wind power in the power system reaches a certain level, it is necessary to properly account for its impact on the planning of power transmission system in order to solve or avoid related problems. The main factors considered in this paper are as follow: 1) Investment budget constraints and investment costs minimization requirements; 2) Impact of wind power output fluctuation on power system security; 3) System adjustment capability and spare capacity requirements; 4) The capability for accommodating wind power.

2.1. Demand-side Response
Traditionally, demand-side load is regarded as a passive and unresponsive one. With the development of power market, the concept of relying on compulsory means to schedule power cuts has been gradually abandoned. The regulation effect of demand-side resources in electricity markets is becoming more and more important. Demand-side response (DR) is a market participation behavior that power users respond to market price signals or incentives, which can change normal power consumption patterns.

Power users are supposed to take actions when electricity price is high or power system reliability is in emergency, so as to alleviate the severe power supply situations. From the perspective of resources, DR is a kind of resource for the effect of peak load or installed capacity reduction; from the perspective of capability, DR can improve the operational reliability of power transmission system and enhance the capability of emergency response; from the perspective of user behavior, DR means the participate in load management and adjustment of power consumption mode.

Demand-side response should be taken into consideration in transmission system planning stage when DR is widely used in the operation of power system. There have been some research work reported in this area. In [9], penalty costs for N-1 expected accidents is calculated as expected value of load shedding amount multiplied by the unit penalty value. Due to the limited peaking capacity and reserve level, the measure of load shedding penalty is not enough to guarantee the safe and stable operation of the power system concerned. In power market environment, it is necessary to introduce DR mechanism for peak-load shifting and change the normal power consumption mode.

Price-based DR is the main form of DR in electricity market, where power users make arrangement and adjustment of power consumption time and mode according to the time or space-based price signals. For another, incentive-based DR is a market-oriented measure where power users are motivated by direct rewards to participate in load adjustment.

Power system is a unified whole composed of power generation, transmission, distribution and consumption. DR can be regarded as a kind of virtual power generation resource, which can provide spare capacity for wind farms and is an effective way to improve the utilization level of wind power.
[7]. In this paper, DR mechanism is introduced in the planning of transmission system with wind farms for the advantages as follows. On the one hand, power load is reduced in case of peak load and shortage of wind power output after a interruptible contract with power users. On the other hand, wind curtailment has to be done in case of valley load and sufficient wind power output, but the introduction of DR can help increase the demand for electricity through electricity price incentive during the valley period, which can improve the utilization level of wind power. Hence, the introduction of DR into transmission system planning problem can help shift peak load, and thus reduce transmission investment cost and improve the utilization level of wind power.

2.2. Capability for Accommodating Wind Power
The adoption of wind power can save the generation cost of thermal power units and reduce sulfur dioxide emissions. Existing research on transmission system planning with wind farms is insufficient in measuring the accommodation capability for wind power and the corresponding social benefits. In the proposed model, power generation of wind farms is maximized during a given period while satisfying safety and reliability constraints of power system. Thus, the proposed model can comprehensively measure the advantages of wind farms in various aspects such as economy and environmental protection.

A bi-level transmission system planning model is proposed in this paper, where demand-side response, wind power accommodation capability are embedded in the transmission system planning optimization problem. In the upper level, the objective is to maximize the generating quantity from wind farms by per unit transmission investment within a given time period. In the lower level, the objective is to minimize the cost for DR and penalty for abandoned wind power in the given time period. These two levels are implemented interactively and iteratively, and the optimal transmission system planning scheme will ultimately be attained by the upper level. The bi-level model has been reported in power system planning area[9], [10].

3. Transmission System Planning Model with Wind Farms

3.1. Upper Level Model

(1) Objective function

The objective function of the upper level model considering DR and capability for accommodating wind power is:

\[ f_1: \quad \max R = \frac{W}{C_L + C_W} \]  
\[ W = \sum_{i\in I} \sum_{j\in N_j} \left( p_{aw}(t) - p_{aj}(t) \right) \Delta t \]  
\[ C_L = \frac{r(1+r)^m}{(1+r)^m - 1} \sum_{i\in I} Z_i \]  
\[ C_W = \sum_{i\in I} \sum_{j\in N_j} \left( \beta_a(t) p_a(t) + \beta_b(t) p_b(t) \right) \Delta t + \sum_{i\in I} \sum_{j\in N_j} K_j p_b(t) \Delta t \]

Where \( R \) is generation quantity from wind farms per unit transmission investment during a given time period, \( W \) is generation quantity from wind farms transferred from the lower level model, \( p_{aw}(t) \) is active power output of wind farm \( j \) during time period \( t \), \( p_{aj}(t) \) is the amount of abandoned power for wind farm \( j \) during time period \( t \), \( \Delta t \) is the duration of period \( t \), which is taken as 1h in case study, \( C_L \) is line investment cost, \( r \) is the discount rate of funds, \( m \) is the number of apportionment years, \( C_{Li} \) is the cost of candidate line \( i \) (¥10000), \( Z_i \) is the number of new lines in the corresponding corridor, \( C_W \) is the sum of DR cost and abandoned wind power cost, which is transferred from the lower level model, \( \beta_a(t) \) is the unit incentive cost of load \( i \) for increasing power demand as needed, \( p_{ai}(t) \) is the power consumption increased by load \( i \) during time period \( t \), \( \beta_b(t) \) is unit compensation cost of interruptible load \( i \) for load shedding; \( p_{bi}(t) \) is the power interrupted during time period \( t \), \( K_j \) is the unit
Cost of abandoned wind power from wind farm \( j \), \( N_B \), \( N_L \), \( N_W \) and \( T \) are candidate line sets, load bus sets, wind farm sets, and scenario sets, respectively.

(2) Constraints

Newly-constructed lines constraint:

\[
0 < Z_i \leq Z_i^{\text{max}}
\]  

Where \( Z_i^{\text{max}} \) is the maximum number of new lines that can be constructed in the corresponding corridor.

### 3.2. Lower Level Model

The lower level model is used to minimize DR cost and abandoned wind power cost.

(1) Objective function

\[
f_2 = \min \left[ \sum_{t=1}^{T} \left( \sum_{i \in N_G} (\beta_{aw}(t)p_{aw}(t) + \beta_{bw}(t)p_{bw}(t)) + \sum_{i \in N_W} K_i p_i(t) \right) \Delta t \right]
\]

(2) Constraints

1) Power flow constraints

The DC power flow model is used in this paper:

\[
P_a + P_w + P_b - P_D - P_s = B\theta
\]

Where \( P_a \), \( P_w \), \( P_b \), \( P_D \) and \( P_s \) are power output vector of conventional power plants, wind farm power output vector, interruptible load vector, abandoned wind power vector, load vector and incentive load vector respectively, \( B \) is bus admittance matrix, \( \theta \) is node voltage phase angle vector, \( f_{ij}(t) \) and \( \bar{f}_{ij} \) are power flow of branch \( ij \) at time \( t \) and the upper limit.

2) Power output constraints of conventional power plants

\[
P_{ga} \leq p_{ga}(t) \leq \bar{p}_{ga}
\]

Where \( p_{ga}(t) \), \( \bar{p}_{ga} \) and \( \bar{p}_{ga} \) are active power output of conventional generator at time \( t \) and its upper and lower limits.

3) Reserve capacity constraints

\[
P_{ga}^{\text{max}}(t) = \min(p_{ga}^{\text{max}}, \alpha_{ga} \times \Delta t + p_{ga}(t))
\]

\[
P_{ga}^{\text{min}}(t) = \max(p_{ga}^{\text{min}}, p_{ga}(t) - \omega_{ga} \times \Delta t)
\]

Where \( N_G \) is conventional power plant sets, \( p_{ga}^{\text{max}}(t) \) is the upper limit of conventional power plant \( k \) at time \( t \), \( p_{ga}(t) \) is the power demand of load \( m \) at time \( t \), \( R_{ga}(t) \) is the lower limit for the positive rotation reserve capacity required at time \( t \), \( \omega_{ga} \) is the climbing rate of conventional power plant \( k \), \( p_{ga}^{\text{min}}(t) \) is the lower limit of conventional power plant \( k \) at time \( t \), \( R_{ga}(t) \) is the lower limit of the negative rotation reserve capacity required at time \( t \), \( \omega_{ga} \) is the landslide rate of conventional power plant \( k \).

4) Demand-side response cost and wind power abandonment constraints

\[
p_{ai}^{\text{min}} \leq p_{ai}(t) \leq p_{ai}^{\text{max}}, \ i \in N_L
\]

\[
p_{bi}^{\text{min}} \leq p_{bi}(t) \leq p_{bi}^{\text{max}}, \ i \in N_L
\]

\[
0 \leq p_{bj}(t) \leq p_{bj}(t)
\]
Where $p_{ait}^{\text{min}}$ and $p_{ait}^{\text{max}}$ are respectively the lower and upper limits of the increasable load of load $i$ at time $t$, $p_{bit}^{\text{min}}$ and $p_{bit}^{\text{max}}$ are respectively the lower and upper limits of the interruptible load of load $i$ at time $t$.

4. Case Study

The modified 18-bus system[10], [11] is employed to demonstrate the performance of the proposed model and algorithm. It is assumed that load rate of each bus is the same at the same time. Detail information about the case is available from the authors upon request.

Take the data of a real wind farm for example, and given the following assumptions: 1) The system needs 9% positive and negative spinning reserve provided by conventional power plants; 2) The failure rate of conventional generators and power lines during each time period is 0.01; 3) The fund discount rate is 10%; 4) The climbing and landslide rates of conventional power plants are 1% of the rated capacity per minute; 5) The funding period for transmission system planning is 20 years; 6) The abandoned wind power penalty for a given wind farm is ¥6,100 / MWh; 7) The number of particle swarms is 50; 8) The maximum number of allowed iterations is 300.

The 18-bus system currently includes 10 nodes and 9 lines. At the end of planning horizon, the system will increase to 18 buses, including 7 power buses and 17 load buses, with a total load of 35,870 MW[10], [11]. The wind farm is located at bus 2, and the wind farm has a rated capacity of 3,600 MW, which accounts for about 10% of the total power load. Each line corridor can be expanded by up to three lines. The unit investment cost for a given line is ¥2 million/km.

Three preferred schemes A, B and C can be obtained by solving the proposed model, as shown in Table 1.

As can be seen from Table 1, all three schemes have wind power abandonment and demand-side response. Compared with scheme B, the investment cost of scheme A is 6% lower, and the demand-side response cost and the abandoned wind power cost is 11.8% lower. However, the sum of line investment cost and operation cost of scheme A is 6.4% lower than that of scheme B, and the annual power generation of wind farm per unit of investment is 6.5% higher than that of scheme B. From this aspect, scheme A is much better than scheme B.

The investment cost of scheme C is the largest, and the demand-side response cost and the abandoned wind power cost are the smallest, which means the highest reliability level. However, the annual power generation of wind farms per unit of investment is the smallest, which indicates that the high investment of scheme C does not bring an expected comprehensive benefit. In contrast, scheme A has the largest target value and is the best among the three.

| Scheme | New line | Number of new lines | $W$ (MW·h) | $C_L$ (¥10,000) | Demand-side response cost (¥10,000) | Abandoned wind cost (¥10,000) | $C_W$ per unit of investment (%) | $R$ (MW·h/¥10,000) |
|--------|----------|---------------------|------------|----------------|-------------------------------|-------------------------------|-------------------------------|------------------|
| A      | 2(1), 5(2), 7(1), 9(1), 10(2), 11(1), 12(2), 13(3), 16(2), 18(1), 19(2), 21(2), 23(3), 25(1), 26(2), 27(3) | 29         | 14321648    | 69161           | 912                           | 2997                         | 5.3%                       | 196              |
| B      | 1(1), 2(1), 3(1), 4(1), 5(1), 7(3), 10(2), 11(2), 12(1), 13(2), 16(2), 18(2), 19(1), 21(3), 22(1), 23(2), 24(1), 25(1), 26(1), 27(2) | 31         | 14357914    | 73602           | 846                           | 3584                         | 5.7%                       | 184              |
| C      | 1(2), 2(1), 5(1), 7(1), 8(1), 14(1) | 34         | 14400197    | 76070           | 962                           | 3868                         | 6%                         | 178              |
5. Conclusion
With the gradual depletion of fossil energy and rapid development of renewable energy, demand-side response and capability for accommodating wind power are introduced into the transmission system planning with wind farms. Demand-side response mechanism is applied to cope with the uncertainty of wind power and optimize the planning scheme, for the effect of peak-load shifting, system flow optimization, transmission system investment reduction, and wind power utilization level improvement. Under the premise of ensuring the reliability of power supply, the utilization level of wind power is improved, transmission line investment plan is optimized, and the economics and reliability of transmission investment is increased. Finally, the essential features of the developed model and adopted algorithms are demonstrated by the modified 18-bus test system. Study results show that demand-side response mechanism can cope with wind power uncertainty and improve the economics of transmission investment and the level of wind power utilization.

References
[1] Renewable Energy Policy Network for the 21st Century[Z]. Renewable global status report, 2010.
[2] A. Wang, et al, "Study on transmission planning of combined wind and storage system." 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2). IEEE, 2018.
[3] Ziaee, Omid, Omid Alizadeh-Mousavi, and F. Fred Choobineh, "Co-optimization of transmission expansion planning and TCSC placement considering the correlation between wind and demand scenarios." IEEE Transactions on Power Systems 33.1 (2018): 206-215.
[4] Y. Zhang, et al, "Transmission planning considering spatial correlation of wind power." Transmission & Distribution Construction, Operation & Live-Line Maintenance (ESMO), 2016 IEEE PES 13th International Conference on. IEEE, 2016.
[5] Baharvandi, Arash, et al, "Bundled generation and transmission planning under demand and wind generation uncertainty based on a combination of robust and stochastic optimization." IEEE Transactions on Sustainable Energy (2018).
[6] H. Zhang, H. Z. Cheng, and S. X. Zhang, "Research on generation and transmission expansion planning with large-scale wind farms integration." 2018 International Conference on Power System Technology (POWERCON). IEEE, 2018.
[7] Praveen, P., et al, "Multi-Objective power system expansion planning with renewable intermittency and considering reliability." 2018 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC) ional conference on computation of power, energy, Information and Communication (ICCPEIC), IEEE, 2018.
[8] Y. Wang, et al, "Transmission planning considering the influence of wind-storage system and technical-economic analysis." 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2). IEEE, 2018.
[9] H. Fan, et al, "Transmission network bi-level programming model considering economy and reliability and hybrid algorithm." Proceedings of the CSEE 16 (2008): 1-7.
[10] J. Zheng, F. S. Wen, and L. Li, "Two-level planning of transmission system with optimal placement of efficient power plant." Electric Power Automation Equipment 33 (2013): 13-33.
[11] X. F. Wang, "Power system optimization planning." China Water & Power Press, 1990.