A Transmission System Planning Method Considering Combined Operation of Wind Farms and Energy Storage Systems

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Abstract. The ever-increasing penetration of wind power has resulted in new problems and challenges to the secure and economic operation of the power system concerned. Given this background, a bi-level transmission system planning model for this purpose is proposed. In the upper level, the objective is to minimize the total cost, the attained transmission planning scheme will be transferred to the lower level. In the lower level, the objective is to minimize the sum of the discharge cost of the energy storage system and the cost of abandoning the wind farm, the discharge cost of the energy storage system and the cost of abandoning the wind farm are transferred to the upper level as feedback. These two levels are implemented interactively and iteratively. Finally, the essential features of the developed model and adopted algorithms are demonstrated by a modified 18-bus test system.

1 Introduction

As the proportion of wind power in the power supply structure continues to increase, its impact on the safe and stable operation of power system is increasingly significant[1]. Wind power fluctuations can be effectively suppressed by combining operation of wind farms and energy storage systems.

For the planning of transmission systems with wind farms, some research has been done 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.

Generally speaking, the existing research on the planning of transmission systems with wind power is relatively preliminary. Given this background, a bi-level transmission system
planning model considering combined operation of wind farms and energy storage systems is proposed.

2 Transmission system planning with wind farms

2.1 Co-operation strategy

Frequent changes in wind speed cause drastic fluctuations in wind farm output power. Energy storage system can suppress power fluctuations. Combined operation of wind farms and energy storage systems is adopted here. On the premise of ensuring the safe and reliable operation of power system, the optimal configuration of the energy storage system capacity allows the output power of the wind farm access point to fluctuate within a given interval. In this way, frequent startup of the energy storage system can be avoided, the depth of discharge of the energy storage system can be reduced, and the cost of the energy storage system can be reduced.

2.2 Characteristics of sodium-sulfur energy storage system

The sodium-sulfur energy storage system is composed of several energy storage units, which stabilize wind power fluctuations by quickly "throughput" power.

(1) Power and electricity of sodium-sulfur energy storage unit

The power \( p_c(t) \) of the sodium-sulfur energy storage unit in the period \( t \) can be described as:

\[
p_c(t) = u_d(t) p_d(t) - u_c(t) p_c(t)
\]

(1)

\[
p_c(t) = \begin{cases} 
\min\{\eta_c M_c(t) p_{dr}, [E_{max} - (1 - \sigma \Delta t) E(t-1)]/\Delta t\} & \text{when } u_c(t) + u_d(t) \neq 0 \\
\sigma E(t-1)/\Delta t & \text{when } u_c(t) + u_d(t) = 0 
\end{cases}
\]

(2)

\[
p_d(t) = \min\{\eta_d M_d(t) p_{dr}, (1 - \sigma \Delta t) E(t-1) - E_{min}] / \Delta t\}
\]

(3)

where \( p_c(t) \) is the charging power of the energy storage unit during time period \( t \), \( p_d(t) \) is the discharge power of the energy storage unit during time period \( t \), \( u_c(t) \) is the charging flag of the energy storage unit during time period \( t \), \( u_d(t) \) is the discharge sign of the energy storage unit during time period \( t \), the value of \( u_c(t) \) during charging is \( 1/0 \), the value of \( u_d(t) \) during charging / discharging is \( 0/1 \), \( \eta_c \) is the charging efficiency of the energy storage unit, \( \eta_d \) is the discharge efficiency of the energy storage unit, \( \sigma \) is the self-discharge rate of the energy storage unit, \( \Delta t \) is the time interval, \( p_{cr} \) is the rated charging power of the energy storage unit, \( p_{dr} \) is the rated discharge power of the energy storage unit, \( E(t-1) \) is the remaining power of the energy storage unit at the end of the \( t-1 \) period, \( E_{max} \) is the maximum allowable remaining power of the energy storage unit, \( E_{min} \) is the minimum allowable remaining power of the energy storage unit, \( M_c(t) \) is the charging power multiple of the energy storage unit during time period \( t \), \( M_d(t) \) is the discharge power multiple of the energy storage unit during time period \( t \).

The stored energy \( E(t) \) of the sodium-sulfur energy storage unit at the end of \( t \) period is:

\[
E(t) = (1 - \sigma \Delta t) E(t-1) + p_c(t) \Delta t - E_i(t)
\]

(4)

\[
E_i(t) = u_d(t) p_d(t) \Delta t - \frac{8 - M_d(t) T_{sd}(t)}{T_{sd}(t)}
\]

(5)

\[
T_{sd}(t) = -3.4497 D_c^i(t) + 21.5962 D_c^2(t) - 45.7961 D_c^3(t) + 34.7117
\]

(6)
where $E_l(t)$ is the power loss when the sodium-sulfur energy storage unit is discharged during time period $t$, $T_{sd}(t)$ is the maximum continuous discharge time length, $D_p(t)$ is the discharge depth of the sodium-sulfur energy storage unit during time period $t$.

(2) Discharge times of sodium-sulfur energy storage unit

The sodium-sulfur energy storage unit can be discharged at high multiples, and its cycle life (the number of discharges) is closely related to the depth of discharge. The sodium-sulfur energy storage unit’s cycle life is inversely proportional to discharge depth. The greater the discharge depth is, the shorter the cycle life of the energy storage system will be. Therefore, in the operation of the energy storage system, it is necessary to avoid deep discharge as much as possible. The expression of the relationship between the cycle life and the discharge depth of the sodium-sulfur energy storage unit at time $t$ is:

$$N_{np}(t) = \frac{4200}{D_p(t)} = \frac{4200}{1 - E(t)/E_R}$$

where $N_{np}(t)$ is the number of dischargeable times corresponding to $D_p(t)$, $E_R$ is the rated capacity of the sodium-sulfur energy storage unit.

3 Transmission system planning model with wind farms

3.1 Upper level model

(1) Objective function

The upper level model aims to minimize the total cost:

$$f_1: \max R = C_L + C_W$$

$$C_L = \frac{r(1 + r)^m}{(1 + r)^m - 1} \sum_{i \in N_b} C_Li Z_i$$

where $R$ is total cost, $C_L$ is line investment cost, $C_W$ is the target value returned by the lower level model, $r$ is the discount rate of funds, $m$ is the number of apportionment years, $C_Li$ is the cost of candidate line $i$ (¥10,000), $Z_i$ is the number of new lines in the corresponding corridor, $N_b$ is candidate line sets.

(2) Constraints

The newly-constructed lines constraint:

$$0 < Z_i \leq Z_i^{\max}$$

where $Z_i^{\max}$ is the maximum number of new lines that can be constructed in the corresponding corridor.

3.2 Lower level model

The lower level model optimizes the capacity of the energy storage system and the charging and discharging strategy. The optimization goal is to minimize the sum of the discharge cost of the energy storage system and the cost of abandoning the wind farm. The objective function of the lower level model is:

(1) Objective function

$$\min C_W = \sum_{i \in T} \sum_{i \in N_s} \frac{u_j(t)w_{si}C_{si}}{N_{npj}(t)} + \sum_{j \in N_w} K_j P_f$$

where $N_s$ and $N_W$ represent the collection of energy storage system and wind farm, respectively, $T$ is the set of study periods, $C_{si}$ is the unit investment cost of energy storage system $i$ (¥10,000), $K_j$ is the wind abandonment penalty coefficient of the
wind farm $j$, $p_j$ is the abandoned wind power (MWh) of the wind farm $j$.

(2) Constraints

1) Power flow constraints

The DC power flow model is used in this paper:

$$P_G + P_W + P_S - p_f - P_D = B \theta$$

(12)

$$f_{ij}(t) \leq |\vec{f}_{ij}|$$

(13)

where $P_G, P_W, P_S, p_f$ and $P_D$ are power output vector of conventional power plants, wind farm power output vector, power output vector of the energy storage system, abandon wind power vector and load vector respectively; $B$ is bus admittance matrix, $\theta$ is node voltage phase angle vector, $f_{ij}(t)$ and $\vec{f}_{ij}$ are power flow of branch $ij$ at time $t$ and the upper limit.

2) Power output constraints of conventional power plants

$$p_{Gi} \leq p_{Gi}(t) \leq \overline{p}_{Gi}$$

(14)

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

3) Reserve capacity constraints

$$\sum (\overline{p}_{Gi} - p_{Gi}(t)) \geq R^+$$

(15)

$$\sum (p_{Gi}(t) - \underline{p}_{Gi}) \geq R^-$$

(16)

Where $R^+$ and $R^-$ are the upper and lower reserve requirements of the system.

4) Load shedding and wind power abandonment constraints

$$0 \leq w \leq P_D$$

(17)

$$0 \leq p_f \leq P_W$$

(18)

5) Charge and discharge constraints of energy storage system

$$M_{ci}^{\min} \leq M_{ci}(t) \leq M_{ci}^{\max}$$

(19)

$$M_{di}^{\min} \leq M_{di}(t) \leq M_{di}^{\max}$$

(20)

$$E_i^{\min} \leq E_i(t) \leq E_i^{\max}$$

(21)

$$E_{i0} \leq E_{iT}$$

(22)

where $M_{ci}(t)$ is the charging power multiple of energy storage system $i$ during time $t$, $M_{ci}^{\max}$ and $M_{ci}^{\min}$ are upper and lower limits, $M_{di}(t)$ is the discharging power multiple of energy storage system $i$ during time $t$, $M_{di}^{\max}$ and $M_{di}^{\min}$ are upper and lower limits, $E_i(t)$ is the amount of energy of the energy storage system $i$ at time $t$, $E_i^{\max}$ and $E_i^{\min}$ are upper and lower limits, $E_{i0}$ and $E_{iT}$ are the power of the energy storage system $i$ at the beginning and end of the research phase, respectively. It can be guaranteed to a certain extent no matter how long the research period is selected, after the end of the period, the energy storage system will not be unable to charge and discharge because its remaining power is too high or too low.

4 Case study

The modified 18-bus system[6], [7] is employed to demonstrate the performance of the proposed model and algorithm. Detail information about the case is available from the authors upon request.
As can be seen from Table I, all three schemes have energy storage systems. The line investment cost of scheme A is 4.3% lower than that of scheme B, and the sum of the discharge cost of the energy storage system and the cost of abandoning the wind farm is 10.5% higher than scheme B. The sum of the discharge cost of the energy storage system and the cost of abandoning the wind farm of scheme B is smaller for the grid structure of scheme A, and then scheme B can tolerate more risk such as lines or generators failure or load fluctuation. However, the total cost of scheme A is 0.6% lower than that of scheme B. From this aspect, scheme A is better than scheme B. The total cost of scheme C is the largest, and the sum of the discharge cost of the energy storage system and the cost of abandoning the wind farm are the smallest, which means the highest reliability level. However, the total cost is the largest, which indicates that the high investment of scheme C does not bring an expected comprehensive benefit. In contrast, scheme A has the smallest target value and is the best among the three.

Table 1. Three network planning schemes for the modified 18-bus system.

| Scheme | New line | Number of new lines | \( C_L \) (¥10,000) | \( C_W \) (¥10,000) | Wind abandonment cost (¥10,000) |
|--------|----------|---------------------|------------------|------------------|-----------------------------|
| A      | 2(1), 5(1), 7(1), 10(2), 11(1), 12(2), 13(1), 16(2), 18(2), 19(2), 21(2), 23(2), 25(2), 26(2), 27(3) | 26 | 56964 | 21435 | 0 |
| B      | 1(1), 2(1), 3(1), 4(1), 5(1), 7(1), 10(2), 11(2), 12(1), 13(2), 16(2), 18(2), 19(1), 21(1), 22(1), 23(2), 24(1), 25(1), 26(1), 27(2) | 27 | 59502 | 19405 | 0 |
| C      | 1(2), 2(1), 5(1), 7(1), 8(1), 10(1), 11(2), 12(1), 13(1), 15(2), 16(2), 18(1), 19(2), 21(1), 22(2), 23(2), 24(2), 25(1), 26(1), 27(2) | 29 | 629095 | 18644 | 0 |

6 Conclusion

Given the background of gradual depletion of fossil energy and rapid development of renewable energy, a bi-level transmission system planning model considering combined operation of wind farms and energy storage systems is proposed.

It is necessary to make trade-offs among line investment cost, wind abandonment and energy storage systems when solving the transmission system planning problem involving wind farms.

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