

The optimal deployment model of energy storage systems considering large-scale wind farms connected

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Abstract. In order to solve the serious wind power curtailment problem caused by the rapid development of large-scale wind power, a multi-point layout energy storage system is proposed in the grid with the large proportion of wind power. Considering the energy storage costs, wind power curtailment costs and the penalty for loss of load, the energy storage planning model is established by introducing the problem of unit commitments with restrictions, which can be solved by using the mature commercial software CPLEX. Finally, taking the standard IEEE 24 node system as an example, different case studies are carried out. It is found that energy storage cost, wind farm location and access power have an important influence on energy storage layout and configuration capacity.

1. Introduction

In recent years, with the rapid growth of wind power installed capacity in the world, wind power has become the main way of human using of clean energy [1]. However, the volatility of wind power output is random and anti-peaking, large-scale wind power curtailment problem is increasing [2-3]. At the same time, due to the restriction of safe and stable operation of power system, the wind farm output is forced to be cut down, and the phenomenon of abandoned wind is generated. The abandonment of wind farm not only causes the waste of energy but also makes the operation of the wind farm difficult to reach the planned utilization hours, which has become a major factor restricting the development of wind power. The energy storage device [4] as the means of transferring electric energy in time, can be introduced into the grid with the large proportion of wind power, which contributes to the large-scale wind power acceptance capacity and reduces wind power curtailment.

Although there are a lot of relevant researches at home and abroad, there are still many problems in energy storage configuration based on improving the new energy acceptance capacity [5-8]. For example, these studies rarely consider the characteristics of energy storage operations. However, the operation characteristics of different energy storage methods vary greatly, and the regulation effect on



wind power is different. The operation mode of the energy storage system is flexible, and different operation modes can be adopted to reduce the wind rejection of the power grid in different scenarios. Therefore, in solving the planning problem of energy storage optimal allocation, considering the actual operation of the energy storage system and adding the corresponding operating conditions constraints, the specific charging and discharging process can be optimized, which can make full use of energy storage capacity.

Based on the above analysis, Considering the energy storage costs, wind power curtailment costs and the operation characteristics of energy storage, the energy storage planning model is established, which can be solved by using the mature commercial software CPLEX. Finally, taking the standard IEEE 24 node system as an example, different case studies are carried out.

2. The optimal deployment model of energy storage systems

There are two main ways to configure energy storage in power grid with wind power: one is to configure it on the wind farm side in order to smooth wind power output; another is to configure it on the appropriate nodes in the grid to improve wind power acceptance capacity by means of Peak load regulation and valley filling. In this paper, the energy storage is mainly aimed at reducing the abandoned wind, so the energy storage is configured in the whole network.

2.1. Objective function

The objective function of the model consists of three parts: investment cost of energy storage system f_{ess} , cost of wind power curtailment f_{wind} and the penalty for loss of load f_{loss} .

$$\min f = \delta_s f_{ess} + \delta_w f_{wind} + \delta_d f_{loss} \quad (1)$$

$$f_{ess} = (1 + r_{op} + r_{ma} + r_{sc}) r_{de} \sum_{k \in \Omega_{es}} (c_p P_{es,k}^r + c_e e_{es,k}^r) \quad (2)$$

$$f_{wind} = \sum_{j \in \Omega_w} \sum_{s \in \Gamma} d_s \sum_{t=1}^T (p_{w,t,s,j}^{\max} - p_{w,t,s,j}) \quad (3)$$

$$f_{loss} = \sum_{m \in \Omega} \sum_{s \in \Gamma} d_s \sum_{t=1}^T (p_{load,t,s,m}^{\max} - p_{load,t,s,m}) \quad (4)$$

In equation (1), δ_s is cost factor of energy storage, δ_w is cost of unit wind power curtailment, δ_d is the penalty factor for loss of load. In equation (2), r_{op} , r_{ma} and r_{sc} are cost conversion coefficients of the operation, maintenance and disposal of the energy storage system. c_p and c_e are the unit power and unit capacity costs of energy storage system. $P_{es,k}^r$ and $e_{es,k}^r$ are the rated power and rated capacity of the energy storage system allocated at the node k . Ω_{es} is the set of energy storage nodes to be configured. In equation (3), Ω_w is the set of wind farms. The letter 's' stands for a typical day, the number of days of which is d_s . T is the number of periods per typical day, Γ is the set of typical days. $p_{w,t,s,j}^{\max}$ and $p_{w,t,s,j}$ are the maximum output and actual output of wind farm j on typical day s within hours t .

2.2. Constraints

The primary constraints of the model include the system DC power flow constraints, conventional power plant operation constraints, wind farm operation constraints, energy storage system operation constraints and system standby constraints.

System power flow constraints

$$P_{g,t,s} + P_{w,t,s} + P_{e,t,s} - AP_{ij,t,s} = P_{load,t,s} \quad (5)$$

$$p_{ij,t,s} - b_{ij} n_{ij} (\theta_{i,t,s} - \theta_{j,t,s}) = 0 \quad (6)$$

$$|p_{ij,t,s}| \leq p_{ij}^{\max} \quad (7)$$

In equation (4), $P_{g,t,s}$, $P_{ws,t,s}$, $P_{e,t,s}$ and $P_{load,t,s}$ stand for output vector of conventional power plant, output vector of wind farm, charge discharge power of energy storage and load active demand vector at each node on typical day s within hours t respectively. A stands for node-to-branch incidence

matrices of lines. $P_{ij,t,s}$ are branch active power vectors of lines on typical day s within hours t respectively. In equation (5), b_{ij} is admittance of branch ij , n_{ij} is the number of line ij . $\theta_{i,t,s}$, $\theta_{j,t,s}$ and $\theta_{ref,t,s}$ are voltage phase angle of bus i , bus j and slack bus on typical day s within hours t respectively. In equation (6), p_{ij}^{max} is the maximum active power limit of branch ij .

Conventional operation constraints

$$\sigma_t p_{g,i}^{\min} \leq p_{g,t,s,i} \leq \sigma_t p_{g,i}^{\max} \quad (8)$$

$$\Delta p_{g,i}^{\min} \leq p_{g,t,s,i} - p_{g,t-1,s,i} \leq \Delta p_{g,i}^{\max} \quad (9)$$

Constraint (7) is the upper and lower bound of the output of conventional thermal power unit. Constraint (8) is climbing and landslide restraint of conventional thermal power unit. σ_t is 0-1 variable standing for the operation state of conventional thermal power unit. Where max and min stand for high/low limit of corresponding variables. $p_{g,t,s,i}$ and $p_{g,t-1,s,i}$ are active power of conventional power plant i on typical day s within hours t and hours $t-1$ respectively, $\Delta p_{g,i}^{\min}$ and $\Delta p_{g,i}^{\max}$ stand for equivalent landslide and climbing rate of conventional power plant i .

$$\sigma_t - \sigma_{t-1} = \zeta_{t-1}^{on} - \zeta_{t-1}^{off} \quad (10)$$

$$\zeta_t^{on} + \zeta_t^{off} \leq 1 \quad (11)$$

$$\zeta_t^{on} + \sum_{k=t+1}^{\min(T, t+T_{min}^{on}-1)} \zeta_k^{off} \leq 1 \quad (12)$$

$$\zeta_t^{off} + \sum_{k=t+1}^{\min(T, t+T_{min}^{off}-1)} \zeta_k^{on} \leq 1 \quad (13)$$

Constraints (10)-(13) are the minimum start-up and shut-down time constraint of thermal power unit. ζ_t^{on} and ζ_t^{off} are 0-1 variables indicating whether to start or stop operation for conventional power plant i at the end of the time interval t . '1' means 'yes', and '0' means 'no'. T_{min}^{on} and T_{min}^{off} are the minimum start-up and shut-down time of thermal power unit.

$$0 \leq p_{w,t,s,j} \leq p_{w,t,s,j}^{\max} \quad (14)$$

$$0 \leq p_{load,t,s,m} \leq p_{load,t,s,m}^{\max} \quad (15)$$

Where $p_{ws,t,s,j}$ is output of wind-storage combined system j on typical day s within hours t .

Energy storage system operation constraints

$$\begin{cases} 0 \leq e_{es,t,s,k} \leq e_{es,k}^r \\ -p_{es,k}^r \leq p_{es,t,s,k} \leq p_{es,k}^r \\ p_{es,k}^{r,\min} \leq p_{es,k}^r \leq p_{es,k}^{r,\max} \end{cases} \quad (16)$$

$$\begin{cases} e_{es,1,s,k} = e_{es,T,s,k} = 0 \\ e_{es,1,s,k} = e_{es,T,s,k} + p_{es,T,s,k} \Delta t \\ e_{es,t,s,k} = e_{es,t-1,s,k} + p_{es,t-1,s,k} \Delta t \end{cases} \quad (17)$$

In equation (16), $e_{es,t,s,k}$ is capacity of energy storage system j on typical day s within hours t . In equation (17), $e_{es,1,s,k}$, $e_{es,T,s,k}$ and $e_{es,t,s,k}$ are storage energy of energy storage system k on typical day s within hours 1, T and t . $p_{es,T,s,k}$ and $p_{es,t-1,s,k}$ are charge-discharge power of energy storage system k on typical day s within hours T and $t-1$. Δt is time interval, 1h.

System standby constraints

$$\begin{cases} \sum_i p_{g,t,s,i}^{\max} + \sum_j p_{w,t,s,j} + \sum_k p_{s,t,s,k} \geq \sum_m p_{load,t,s,m} + R_{u,t}, \\ \sum_i p_{g,t,s,i}^{\max} + \sum_j p_{w,t,s,j} + \sum_k p_{s,t,s,k} \geq \sum_m p_{load,t,s,m} - R_{d,t}. \end{cases} \quad (18)$$

Where $R_{u,t}$ and $R_{d,t}$ are the positive and negative rotating reserve capacity limit within hours t . The objective function consists of equations (1)-(4), and the constraints consists of equations (5)-(18). The case has been implemented on a personal computer, using CPLEX under MATLAB.

3. Case study

3.1. Example system settings

This paper takes the IEEE 24 bus system as an example system [9]. System parameters are available in the literature [9]. Suppose that all the load and power capacity of the system are increased to 3 times of the original value, and the maximum total load is increased to 8550MW. On this basis, 7 new transmission lines are added to increase the transmission capacity of the system. The new lines are respectively : 6-10(1)、7-8(2)、10-12(1)、14-16(1)、16-17(1)、20-23(1). Among them, 6-10 (1) indicates that 1 line is added to the branch 6-10. Assume that nodes 3, 4, 5, 6, 8, 9, 10 are allowable building points for energy storage. The compressed-air system is selected as the energy storage system, and cost parameters [10] of which are shown in Table 1. The time series datas of wind power output and load demand are shown in figure 1.

Table 1. The cost parameters of energy storage system.

| r_{op} | r_{de} | $c_p(\text{RMB/kW})$ | $c_e(\text{RMB/kWh})$ |
|----------|----------|----------------------|-----------------------|
| 0.01 | 0.05 | 200 | 4000 |

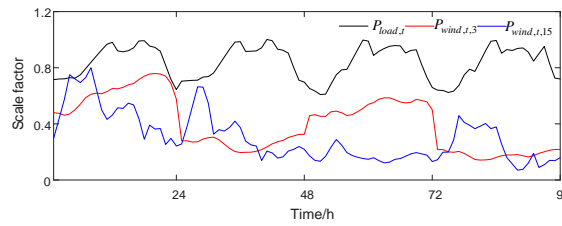


Figure 1. Wind power output and load demand.

3.2. Planning result analysis

3.2.1. Influence of energy storage cost on deployment of energy storage

Two wind farms are connected to nodes 3 and 15 respectively, and the integration power is 1400MW and 300MW respectively. Considering that the energy storage cost has an important influence on the results of deployment of energy storage, this section changes the value of the energy storage cost coefficient δ_s , then solve the model and obtain planning results as shown in table 2 and figure 2. The results show that with the decrease of energy storage cost coefficient δ_s , the energy storage planning power increases gradually and the cost of wind power curtailment gradually becomes smaller. In addition, when the energy storage cost coefficient drops to 0.6, the effect of reducing wind power curtailment is significant.

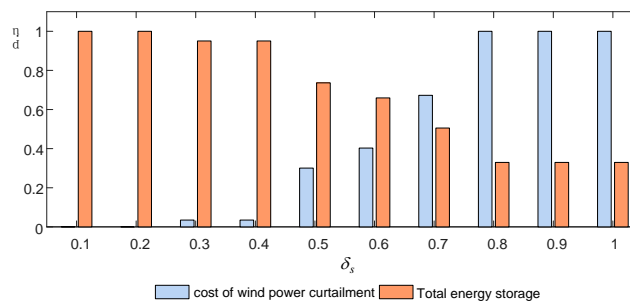
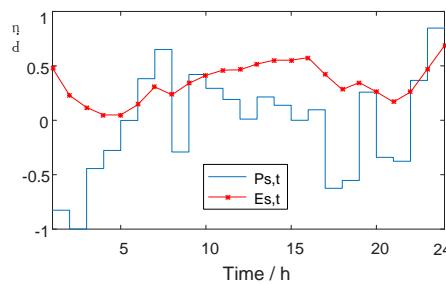


Figure 2. Cost of wind power curtailment and total energy storage under different δ_s .

Table 2. Planning schemes under different δ_s .

| δ_s | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
|-------------------------------------|---------------------------|-------------------------|---------------------|--------------|-------|-------|
| Location/power(MW) of Stored energy | 3/120; 4/120; 8/120;9/120 | 3/120; 4/4; 8/120;9/120 | 3/120; 8/106; 9/120 | 3/120; 9/120 | 3/120 | 3/120 |
| Total energy storage/MW | 480 | 364 | 346 | 240 | 120 | 120 |
| f_{wind} /Million RMB | 0 | 0.02 | 1.21 | 13.92 | 34.53 | 34.53 |

Influence of wind power integration power on deployment of energy storage In this section, the value of the cost coefficient of energy storage is set to 0.5. In order to analyze the deployment of energy storage under different wind power integration power, two wind farms are connected to nodes 3 and 15 respectively, and the node 15 wind farm power is fixed to 300MW while the node 3 wind farm power is changed, then solve the model and obtain planning results as shown in table 3. The curve of energy storage operation under scenario 1 is shown in figure 3($P_{w,3}=1400\text{MW}$). Analysis of Table 3, it can be found that with the increase of wind power integration power, the total power of energy storage gradually increases. However, the cost of wind power curtailment is not a monotonic change. This is because the results of the optimization model are achieving comprehensive optimization between the cost of energy storage and cost of wind power curtailment.

**Figure 3.** The curve of energy storage operation under scenario 1.**Table 3.** Planning schemes under different $P_{w,3}$.

| $P_{w,3}$ /MW | 1100 | 1200 | 1300 | 1400 |
|--|------|------|-------|--------------------|
| Location/planning power(MW) of Stored energy | - | 3/12 | 3/110 | 3/120; 8/28; 9/120 |
| Total energy storage/MW | 0 | 12 | 110 | 268 |
| f_{wind} /Million RMB | 0 | 0.07 | 0 | 10.3 |

Influence of wind power integration position on deployment of energy storage In this section, the value of the cost coefficient of energy storage is set to 0.5. The node 15 wind farm integration power is fixed to 300MW, another wind farm integration power is set to 1400MW. Changing its integration position, solve the model and obtain planning results as shown in table 4. The results show that when the total wind power integration power of the system is certain while wind power integration position changing, deployment of energy storage is different, and the cost of wind power curtailment is also different. However, the energy storage systems are the preferred configuration in the wind farm side to enhance the capacity of wind power utilization.

Table 4. Planning schemes when changing wind power integration position.

| Wind power integration position/MW | 3 | 6 | 13 |
|--|--------------------|------------|-------------------|
| Location/planning power(MW) of Stored energy | 3/120; 8/28; 9/120 | 5/8; 6/120 | 5/16; 9/84; 10/26 |
| Total power of energy storage/MW | 32.48 | 15.51 | 15.27 |
| f_{wind} /Million RMB | 10.3 | 12.41 | 25.05 |

4. Conclusion

The abandoned wind caused by the wind power output characteristics and power system operation constraints is an important issue for the development of wind power. Based on the characteristics of energy storage operation, the optimal allocation model of energy storage is established to reduce the abandoned wind. The effect of energy storage on reducing the abandoned wind is verified by comparing planning results under different energy storage cost, wind power integration power and position. The results show that as the cost of energy storage decreases, the role of energy storage in reducing abandoned wind will be more pronounced. In addition, with the energy storage to reduce the cost of storage can reduce the abandoned wind effect is more obvious; the storage layout in the whole network is more conducive to play the energy adjustment ability, promote the wind power accommodation. More importantly, the multi-point energy storage layout in the whole network is more conducive to play the role of energy storage regulation.

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