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Optimal Configuration of Large-Scale Storage Energy Access to Actual Power Grid with High Wind Power Proportion

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Abstract. In order to solve the problem of abandoned wind power in new energy high permeability grid, a large-scale energy storage device optimization configuration algorithm is proposed. At the same time, the energy storage cost, the abandonment cost and the loss of load cost are taken into consideration, and an optimization model is established considering various operational constraints and solved through the mature commercial software CPLEX. Finally, the 750kV system obtained by the actual grid equivalent is taken as an example to obtain an optimal configuration scheme for energy storage in the actual power grid.

1. Introduction

In order to coordinate the contradiction between energy and the environment, countries around the world have made great progress in new energy technologies [1]. However, there are many problems in the grid connection of new energy power generation, especially large-scale wind turbines. At the same time, due to the stable operation of the system, the wind farm is forcibly limited, resulting in the occurrence of wind abandonment. Due to its space-time characteristics, the energy storage device can realize the time transfer of energy. When applied to the power grid, it can smooth the fluctuation of wind power output, which is conducive to the grid to absorb wind power output [2].

Although domestic and foreign scholars have carried out related research, there are still many problems and deficiencies [3-7]. For example, the existing research content is rarely based on large-scale power grids. Most studies use mature classic examples. With the continuous development of energy storage technology, it is foreseeable that the installed capacity of energy storage devices in the power grid will continue to increase [8]. It is more practical to study the optimal configuration of energy storage based on actual power grids.

In summary, this paper treats an actual grid equivalently into a 750kV backbone grid for energy storage optimization configuration research, with the lowest energy storage cost and abandonment cost as the optimization goal, fully considering the operational characteristics of energy storage and grid operation. Through the commercial software CPLEX, which has been matured in various fields, the problem of optimal energy storage configuration under different schemes is studied.

2. Actual grid equivalence

Since the actual power system generally gives the node injection power instead of the node injection current, the WARD equivalent method should be processed when the actual power system performs the equivalent calculation.

Due to the relationship between current and power:

$$\dot{\mathbf{I}} = \hat{\dot{\mathbf{E}}}^{-1}\hat{\dot{\mathbf{S}}} \tag{1}$$

In this formula, $\hat{\dot{S}}$ Is the conjugate of the node injection power;

$$\hat{\dot{\mathbf{E}}}^{-1} = \mathrm{diag}\left[\hat{\dot{\mathbf{V}}}_{\mathrm{i}}^{-1}\right] \tag{2}$$

In this way, the boundary current injection current formula of the original WARD equivalent becomes:

$$\tilde{\dot{\mathbf{I}}}_B = \dot{\mathbf{I}}_{\mathbf{B}} - \mathbf{Y}_{BE}\mathbf{Y}_{EE}^{-1}\dot{\mathbf{I}}_E = \hat{\dot{\mathbf{E}}}_B^{-1}\hat{\dot{\mathbf{S}}}_B - \mathbf{Y}_{BE}\mathbf{Y}_{EE}^{-1}\hat{\dot{\mathbf{E}}}_E^{-1}\hat{\dot{\mathbf{S}}}_E \tag{3}$$

From the above method, the equivalent processing of an actual system is obtained, and the equivalent data of the 750kV backbone network is obtained.

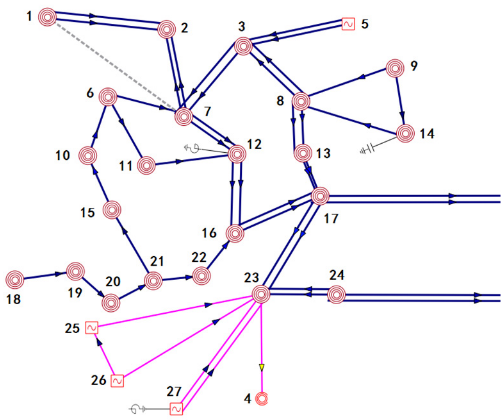

Figure 1. Equal value 750 kV main net

3. Optimal configuration model for large-scale energy storage systems

In the research work of this paper, the energy storage is configured at the appropriate node on the grid side to reduce the abandoned wind rate.

3.1. Objective function

The purpose of this paper is to reduce the rate of abandoned wind, but the wind power volatility and its anti-peak characteristics make the peaking capacity and spare capacity requirements of the grid after the large-scale wind power is connected to the grid, and to meet various limit conditions, consider resection. A small amount of load to meet the system's stable operation requirements.

Therefore, the objective function of this model is divided into 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}.

$$\min f = \delta_s f_{ess} + \delta_w f_{wind} + \delta_d f_{loss} \tag{4}$$

$$\begin{cases} f_{ess} = \sum\limits_{k\in\Omega_{es}} (c_p p_{es,k}^r + c_e e_{es,k}^r)/Y_{ear} \\ f_{wind} = \sum\limits_{j\in\Omega_w}\sum\limits_{s\in\Gamma} d_s \sum\limits_{t=1}^{T} (p_{w,t,s,j}^{\max} - p_{w,t,s,j}) \\ f_{loss} = \sum\limits_{m\in\Omega}\sum\limits_{s\in\Gamma} d_s \sum\limits_{t=1}^{T} (p_{load,t,s,m}^{\max} - p_{load,t,s,m}) \end{cases} \tag{5}$$

In equation (4), 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 (5), c_p 、 c_e are the unit power and unit capacity costs of energy storage system, Y_{ear} is the effective life of the energy storage equipment, $p^r_{es,k}$ and $e^r_{es,k}$ 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. 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. $p^{\max}_{w,t,s,j}$ and $p_{w,t,s,j}$ are the maximum output and actual output of wind farm j on typical day s within hours t.

3.2. Constraints

The constraints of the model include: system power flow constraints, conventional unit operation constraints, wind farm operation constraints, energy storage system operation constraints, and system backup constraints.

System power flow constraints:

$$\boldsymbol{P}_{g,t,s} + \boldsymbol{P}_{w,t,s} + \boldsymbol{P}_{e,t,s} - \boldsymbol{A}\boldsymbol{P}_{ij,t,s} = \boldsymbol{P}_{load,t,s} \tag{6}$$

$$\begin{cases} p_{ij,t,s} - b_{ij} n_{ij} (\theta_{i,t,s} - \theta_{j,t,s}) = 0, \\ \left| p_{ij,t,s} \right| \le p_{ij}^{\max} \end{cases} \tag{7}$$

In equation (6), $\boldsymbol{P}_{g,t,s}$ 、 $\boldsymbol{P}_{w,t,s}$ 、 $\boldsymbol{P}_{e,t,s}$ and $\boldsymbol{P}_{load,t,s}$ 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. $\boldsymbol{A}$ stands for node-to-branch incidence matrices of lines. $\boldsymbol{P}_{ij,t,s}$ are branch active power vectors of lines on typical day S within hours t respectively. In equation (7), $p_{ij}^{\max}$ is the maximum active power limit of branch ij. b_{ij} is admittance of branch ij, n_{ij} is the number of line ij. $\theta_{i,t,s}$ and $\theta_{j,t,s}$ are voltage phase angle of bus i and bus j on typical day s within hours t respectively.

$$\begin{cases} 0 \le p_{w,t,s,j} \le p^{\max}_{w,t,s,j} \\ 0 \le p_{load,t,s,m} \le p^{max}_{load,t,s,m} \end{cases} \tag{8}$$

In equation (8), $p_{w,t,s,j}$ and $p^{\max}_{w,t,s,j}$ are wind farm j actual output of wind in the period t of the typical day s.

Conventional operation constraints, system standby constraints and energy storage system operation constraints are available from references [1-2].

This paper uses YALMIP to call the CPLEX solver to solve the operation on the MATLAB R2014a platform. The objective function and constraints are as shown in the above formula to ensure the safe and stable operation of the system.

4. Case study

4.1. Example system settings

This paper takes a 750kV network system obtained by using an actual power grid equivalent as an example system, to study the optimal allocation scheme of large-scale energy storage system in the grid considering wind power access. In the example, the energy storage system selects the battery energy storage, and its cost parameters are shown in Table 1.

Table 1. The cost parameters of energy storage system.

r_{op}	r_{de}	c_p(RMB/kW)	c_e(RMB/kWh)
0.01	0.05	200	4000

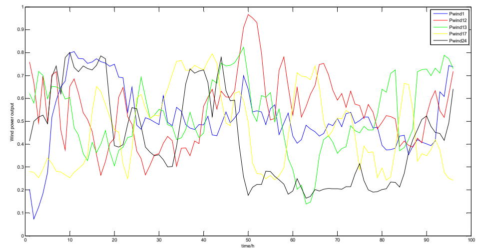

Figure 2. Wind power output

The actual grid system is equivalently treated as a 750kV backbone network with 27 nodes and 31 branch systems. The network topology is shown in Figure 1. Combined with the purpose of this paper, this paper connects the wind farms at nodes 1, 12, 13, 17 and 24 to explore the optimal configuration results under different conditions.

It is assumed that nodes 1, 5, 6, 7, 10, 11, 12, 13, 15, 16, 17, 19, 20, 23, 24 are energy storage allowable construction points, and the system can build up to 8 energy storage power stations.

4.2. Planning result analysis

The energy storage cost factor is 0.4. In order to analyze the energy storage configuration under different wind power access powers, this section accesses 5 wind farms at nodes 1, 12, 13, 17, and 24 respectively. The access power of nodes 1, 12, 13, and 17 is fixed at 1800 MW and 1800 MW. 1800MW, 2000MW, change the access power of the wind power of the node 24, and solve the model to obtain the results shown in Table 2.

Table 2. Planning schemes under different $P_{w,24}$.

$P_{w,24}$/MW	500	1000	1500	2000
Location/planning power(MW) of Stored energy	1/177.3	1/263.8	1/314.7	1/481.1
	6/97.1	5/260.4	7/168.1	5/269.2
	10/89.5	10/210.9	11/430.3	10/291.5
	13/239	12/190.4	15/157.3	13/575.2
	16/275.6	15/194.9	17/466.5	17/669.7
	24/241.1	20/231.3	24/541.1	24/451.1
		24/247.2		
Total energy storage/MW	1119.6	1598.9	2078	2737.8
f_{wind} /Million RMB	275.1	257.8	243.9	170.5

Similarly, the power of several other wind farms (1, 12, 13, 17) was changed to explore the impact of different wind farm access power on optimal energy storage configuration.

Table 3. Planning schemes under different $P_{w,17}$.

$P_{w,17}$/MW	500	1000	1500	2000
Location/planning power(MW) of Stored energy	1/187.3	1/54.2	1/211.2	1/481.1
	6/214.7	5/391.5	7/437.2	5/269.2
	11/138.5	10/187.6	11/307.2	10/291.5
	13/88.7	12/238.2	15/268.2	13/575.2
	16/153.8	16/131.7	17/485.2	17/669.7
	20/198.7	20/260.3	24/323.3	24/451.1
	24/0.857	24/244.1		
Total energy storage/MW	982.6	1507.6	2032.3	2737.8
f_{wind} /Million RMB	117.0	140.4	185.2	170.5

Table 4. Planning schemes under different $P_{w,13}$.

$P_{w,13}$/MW	500	1000	1500	2000
Location/planning power(MW) of Stored energy	1/281.9 5/298.3 10/166.1 12/263 15/210.4 20/240.6 24/198.1	1/314.7 7/216.6 11/347.4 15/211.5 17/510.1 24/422.9	1/285.6 6/560.6 11/109.4 13/445.3 17/521.7 24/529.4	1/431.3 7/397.1 12/700 16/700 24/700
Total energy storage/MW	1658.4	2012.3	2452	2928.4
f_{wind} /Million RMB	138.95	165.4	168.7	173.8

Table 5. Planning schemes under different $P_{w,12}$.

$P_{w,12}$/MW	500	1000	1500	2000
Location/planning power(MW) of Stored energy	1/232.8 7/213.5 11/311.1 15/471.7 17/456.3 24/358.1	1/329.5 6/576.6 11/447.6 15/521 17/207.8 24/158.6	1/192.3 6/333.3 11/635.4 13/496.1 17/545.4 24/236.1	1/626.4 7/533.3 12/700 16/602.2 24/552.9
Total energy storage/MW	2043.5	2241.1	2438.6	3014.8
f_{wind} /Million RMB	306.2	276.9	250.1	87.1

4.3. chapter summary

Based on the data in the above experimental results, when the wind farm access power changes, the number of nodes recommended by the energy storage system optimization configuration results is as shown in the Figure3:

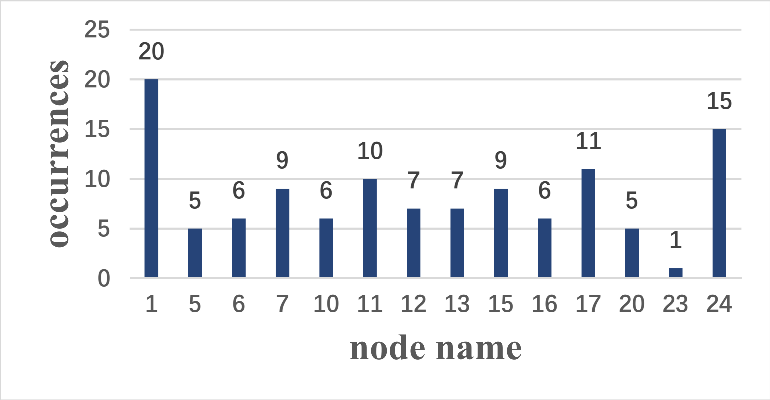

Figure 3. Recommended node occurrences

The recommended nodes for the installation of energy storage in the example grid are given by the frequency of the recommended nodes in Figure3 (in order of the recommended nodes appearing from high to low): 1, 24, 17, 11, 7, 15, 12, 13, 6, 10, 16;

Considering that in actual operation, the energy storage access node generally selects the low voltage level node instead of directly accessing the 750kV voltage side, and considers the feasibility factors of the actual installation of the large scale energy storage device in the substation. Therefore, the recommended placement and storage are given. When the location is available, in the above-mentioned recommended nodes, according to the actual grid situation, a node with sufficient feasibility and close to the wind power collection area is selected to configure the energy storage.

Combining the results of energy storage nodes and capacity allocation in the results of previous simulation experiments, combined with the actual grid operation, the recommendations for the configuration of the above 10 final recommended locations for energy storage are respectively: 1, 24, 17, 13, 12, 10, 16 .The capacity configuration is recommended to be 500MW, 500MW, 700MW, 600MW, 200MW, 300MW, 200MW, and the total configuration capacity is 3000MW.

5. Conclusion

The abandoned wind power caused by wind power output characteristics and power system operation restrictions is an important issue wind power development faced with. In this paper, based on the energy storage operation characteristics, an energy storage optimization configuration model aiming at reducing wind abandonment is established. By comparing different wind power access locations, access power and different energy storage cost coefficients, the effect of energy storage on reducing wind abandonment is verified.

The results of the example show: With the reduction of energy storage costs, the effect of energy storage on reducing the power of abandoned wind power is more significant; the layout of energy storage multi-points in the whole network is more conducive to the performance of energy storage regulation and promoting the consumption of wind power.

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