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Research on the optimal configuration method of energy storage based on wind power randomness

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Abstract. Large-scale wind power integration into the power grid will bring some negative effects or even large faults to the power system, such as voltage instability, the change in the transient stability of the system, etc. This could lead to the low accuracy of the wind power prediction results and the unreasonable capacity configuration of the energy storage. In this paper, considering the uncertainty of wind power, the optimization model of minimizing the operating cost, voltage deviation, and pollutant emission is constructed. Additionally, the mixed probability optimization algorithm (PLF-NSGAII-MOPSO) is calculated and analyzed. The results show that the method proposed in this paper is beneficial to finding the optimal configuration of energy storage under the condition of wind power access.

1 Introduction

Energy storage is a technical means to improve the efficiency of new energy utilization and the reliability of power supply, which is highly recognized by China's energy authorities. How to plan the energy storage capacity is an urgent problem to be solved. Due to the high cost of energy storage, various factors need to be taken into account combined with the requirements of power grid operation control. In the process of system construction [1], there is a need to optimize the capacity configuration of the energy storage system from factors such as economic investment restriction and technical reliability restriction, and finally determine a reasonable construction scale.

The problem of optimal energy storage configuration means the minimization of investment costs and the expected operating costs. By increasing energy storage capacity, investment costs are increased, but system operating costs are reduced [2]. This paper analyzes the economy of hybrid energy storage and the power fluctuation stabilization effect of grid-connected microgrids and proposes the optimal configuration method of hybrid energy storage capacity based on non-cooperative games [3,4]. Combined with the configuration of new energy storage in western China as a case, LCOS is the main line to quantitatively analyze the cost trend of various energy storage technologies in new energy consumption application scenarios [5, 6]. In general, energy storage access will increase the operating cost and voltage distribution of the power system. In addition, the increase in permeability of wind energy, due to its economic and environmental advantages, also aggravates the challenge [7, 8]. The high investment cost of wind power generation connected to energy storage requires accurate modeling and optimization of energy storage capacity to achieve economic and reasonable operation [9, 10].

This paper adopts the method of Wilson distribution and five-point discrete distribution to model wind power uncertainty. The MOPSO-NSGA _ II combined with the probability power flow (PLF) hybrid algorithm is used to solve the model. It aims to expect the presence of power system operating conditions, find the optimal location and capacity of energy storage configuration, help to minimize the investment and operation cost, and optimize the intermittent voltage deviation and pollutant emission level of wind power generation.

2 Uncertainty modeling of wind power generation

Stochasticity and uncertainty are two major challenges for wind energy resource applications, which increase the uncertainty of the generation side system [11]. To overcome the variability of wind energy, energy storage to balance output equipment can be used. Overcoming the unpredictability of wind energy requires some modifications to deterministic decisions and the application of new scenario-based technologies.

2.1 The Weibull distribution

Weibull probability distribution function and Rayleigh model are common methods for wind speed modeling. However, the Weibull distribution function is more general and has a higher accuracy. The mathematical form of the Weibull distribution function applied to the wind speed prediction is expressed as formula (1):

$$f(v \mid \lambda, k) = \left(\frac{k}{\lambda}\right)\left(\frac{v}{\lambda}\right)^{k-1} e^{-\left(\frac{v}{\lambda}\right)} \quad (1)$$

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$k > 0, \lambda > 0$, Among them, v represents wind speed (m/s). The k is the dimensionless shape coefficient, and the λ is the same as the v units.k,λ are solved in different ways, among which the most general one is the moment method, with the following formula (2):

$$\bar{v} = \lambda.\Gamma\left(1 + \frac{1}{k}\right) \& k = \left(\frac{0.9874}{\frac{\sigma}{\bar{v}}}\right)^{1.0983} \quad (2)$$

The analysis of the probabilistic load flow requires data on wind power generation. For this, variable wind turbines are often abstracted as a particular curve, To represent the internal logic between the wind speed and the power quantity, the following formula (3):

$$Y = \begin{cases} 0 & X \le v_{ci}\, or X \ge v_{co} \\ \alpha + \beta X & v_{ci} \le X \le v_{co} \\ M & v_{no} \le X \le v_{co} \end{cases} \quad (3)$$

where *Y, X,* and *M* are the Input power, wind speed, and maximum generating power. α And β are the linear parameters.v_{ci}, v_{co} and v_{no} Represents Cut-in wind speed, cut-out wind speed, and normal wind speed.

2.2 Discrete wind power output characteristics

Abstracting the continuous probability distribution of wind power output into discrete distributions can effectively improve the simplification of random load calculation. Therefore, we can replace the continuous functions with a five-point discrete function.

This paper takes the typical daily wind speed data of A city in western China in recent 10 years as sample data and analyzes the Weibull distribution function. The rated wind power generation is 113 MW (total maximum load of 283 MW), with a penetration rate of 40%. Five-point discrete distributions are presented in Table 1.

Table 1. Five-point discrete estimates of wind power generation.

Wind power (MW)	0	14.53	55.78	98.13	113.2
Probability (%)	6.89	20.45	40.47	19.91	12.28

3 Construction of energy storage optimal configuration model

The optimal layout and scale of energy storage are rich, and minimizing operating cost, voltage deviation and pollutant emission are the key goals.

Operating cost minimization refers to the total operating cost of all wind turbines at random output power based on the optimal configuration of energy storage and specific wind power plants [12]. The second goal is to minimize the voltage deviation, which is due to the considerable fluctuations of the bus voltage with the change of wind power generation, resulting in an unsatisfactory voltage distribution curve. The third goal is to minimize pollutant emissions, whose boundary conditions are consistent with the first goal.

3.1 Objective function

The objective function for constructing the optimal energy storage configuration in the power system is as formula (4):

$$\begin{aligned} minf_1 &= \textstyle\sum_5^{i=1} Prob_i \cdot Cost_i \\ minf_2 &= \textstyle\sum_5^{i=1} Prob_i \cdot \left(\sum_n^{k=1}\left(\frac{v_{k,i} - v_{k,i}^{spc}}{\Delta v_{k,i}^{max}}\right)^2\right) \\ minf_3 &= \textstyle\sum_5^{i=1} Prob_i \cdot Emission_i \end{aligned} \quad (4)$$

$Prob_i$ is the probability of the i th case; n is the total number of buses; $v_{k,i}$ is the voltage of the bus k in the i th case. $v_{k,i}^{spc}$ is the expected voltage in the third case; $\Delta v_{k,i}^{max}$ is the maximum voltage deviation in Scenario i, or about 0.12 pu; according to the voltage constraint range; $Cost_i$is the total operating cost ($ / h) in the third case.

3.2 Constraints

(1) Power balance constraint

The total generation of the plant shall be equal to the load demand of the grid and shall consider the power loss with the following formula (5):

$$\textstyle\sum_{NG}^{j=1}\left(P_{i,j}\right) + P_{i,\,wind} + P_{i,\,storage} - P_D - P_{i,\,Loss} = 0 \quad (5)$$

P_D, Total load demand (MW); P_{Loss}, Power grid line loss (MW).

(2) Power generation capacity constraints

Under the normal operation conditions of the system, the output of each unit shall be between P_j^{min} and P_j^{max} . as shown in formula (6)

$$P_j^{min} \le P_j \le P_j^{max} \quad j = 1,2 \ldots NG \quad (6)$$

(3) Slope rate constraint

The slope constraint for the k th cell, reflecting the maximum generation variation between time intervals. as shown in formula (7):

$$\begin{aligned} P_{k,t-1} - P_{k,t} &\le DR_k \\ P_{k,t} - P_{k,t-1} &\le UR_k \end{aligned} \quad (7)$$

UR_k, DR_k represents the upper and lower limits of the rated power generation of the k-th unit respectively.

(4) Power flow equation constraint

Based on the Newton-Rafson method, as shown in formula (8):

$$\begin{cases} P_m - V_m \sum_N^{n=1} V_n (G_{mn}\cos\,\delta_{mn} + B_{mn}\sin\,\delta_{mn}) \\ Q_m - V_m \sum_N^{n=1} V_n (G_{mn}\sin\,\delta_{mn} - B_{mn}\cos\,\delta_{mn} \end{cases} \quad (8)$$

P_m, Q_m represent the active and reactive power of the bus m.V_m, G_m, B_{mm} Represents bus voltage, conductance, and susceptance between bus m and bus n, respectively δ_{mn} shows the angular difference of the voltage in the bus line m and n.

(5) Voltage, transformer tap, and energy storage configuration capacity boundary

These boundary conditions are coupled with bus voltage, generator reactive power and transformer tap, as shown in formula (9):

$$\begin{cases} V_{\min} \le V_n \le V_{\max} \\ T_{\min} \le T_i \le T_{\max} \\ Q_{G\min} \le Q_{Q_i} \le Q_{G\max} \\ 0 \le P_{storagei} \le P_{storagemax} \end{cases} \quad (9)$$

V_n is the root mean square of the nth bus voltage; T_i, Q_{Q_i} are the tap of Transformer i and the reactive power of Generator i; The maximum capacity of each node is 20 M.

4 Hybrid probability optimization algorithm (PLF-NSGAII-MOPSO)

The solution presented in this section is a hybrid algorithm resulting from a combination of multi-objective NSGAII-MOPSO, algorithm and the newly proposed probabilistic load flow PLF to determine the optimal location and the power rating of the energy storage configuration. The method can be written and performed in MATLAB software and calculated using the Newton-Raphson method, with the objective function and solving the above constraints. First, the algorithm randomly initializes bus voltage, the generator output power, and the Energy storage configuration point and capacity [13], then evaluates the objective function through the probabilistic load flow, and invokes the best position associated with the best fitness value. If the algorithm has not yet searched for the optimal combinatorial objective function, the position and speed of each particle will be continuously updated. Create a new population for the next cycle by combining the pre- and post-update elements and selecting the best solution from the representative set.

5 Simulation and results

5.1 Parameter setting

The model is made up of five generators on Buses 1, 5, 8, 11 and 13. The bus voltage is limited between 0.94 and 1.06 PU. Bus 1 is a standard bus, while Buses 5, 8, 11, and 13 are voltage-controlled and the other buses are load-type. Wind turbines with a rated capacity of 113 MW are also added on bus line 2. Taking the Madison load map as an example, the maximum load is 283.4 MW as the peak load condition, but no operational constraints and charge-discharge strategies are considered.

This section assumes that the operating cost of the wind turbine is 30$/Mwh and that the operation and maintenance of the energy storage system is 40$/Mwh. Data parameters for the generator set are shown in Table 2. For Scenarios 1, 2, and 3, there are no other constraints except for the maximum generation constraint of the thermal power unit.

Table 2. 30 Power generation unit data of the node system.

Generatrix	Minimum power (MW)	Maximum power (MW)	P0 (MW)	Rup (MW)	Rdown (MW)	PZ(MW)	a($/h)	b ($/M wh)	c ($/Mw2 h)	α (Kg/h)	β (Kg/M wh)	γ (kg/mw 2h)
1	40	250	135	60	90	[60 70], [190 210]	270	30	0.0354	42.89	-0.5271	0.00461
2	A 113-megawatt wind power station											
5	30	180	110	70	85	[50 65], [120 130]	360	41	0.0211	41.75	-0.5116	0.00438
8	20	100	40	30	40	[40 60]	350	40	0.0179	40.55	-0.3630	0.00571
11	30	150	100	40	70	[35 40], [110 125]	340	39	0.0280	40.26	-0.5455	0.00683

5.2 Case analysis

This section sets up four scenarios as follows.

Scenario 1: Normal probability power flow analysis, considering wind power, excluding energy storage.

Scenario 2: Optimal trend analysis, considering the amount of electricity and energy stored in the system.

Scenario 3: Select the intelligent algorithm to consider wind power and energy storage, but ignore the constraints of generating capacity, forbidden area, and climbing rate.

Scenario 4: Similar to Scenario 3, consider the comprehensive generator set constraints.

(1) Scenario 1: Power power flow analysis

The operating cost, voltage deviation, and pollutant discharge of the generator set are shown in Table 3. As wind power generation increases, system operating costs, pollutant emissions, and power losses are all decreasing. The operating cost of the system was reduced from 13,462$ / h to 11,435$ / h, and wind energy generation was increased from 0 to 113 MW. In addition, the power system also has a voltage drop and over-voltage situation. In the Buses 11 and 13, voltages are 1.082 and 1.071 per unit, respectively.

Table 3. Simulation results for Scenario 1.

Wind power generation capacity (MW)	0	14.49	55.81	97.11	112.12
Probability (%)	6.79	20.39	40.46	19.88	12.30
Operating cost ($ / h)	13256	13064	12320	11711	11540
Voltage deviation	2.59	2.61	2.72	2.79	2.84
Emission (Kg / h)	370.11	341.39	276.61	227.71	213.81
Loss (MW)	15.24	14.30	12.09	10.46	9.89
Bus line 1 (MW)	258.60	243.17	199.69	154.62	139.31
Bus line 5 (MW)	10.01	10.02	10.12	10.09	10.11
Bus line 8 (MW)	10.02	10.03	10.13	10.09	10.09
Bus-line l1 (MW)	10.12	10.01	10.11	10.10	10.12
Bus-line l3 (MW)	10.03	10.13	10.12	10.11	10.13
Average operating cost ($ / h)			12313		
Average voltage deviation of (%)			2.731		
Average emission (Kg / h)			279.12		

(2) Scenario 2: Optimal trend analysis

When wind power generation is 0 MW, the classical optimal power flow analysis method is used to find the size and position of the energy storage configuration, and the system is analyzed according to the obtained energy storage configuration. Simulation results are shown in Table 4. Nodes 7,19,21,24 and 30 are considered optimal for energy storage configuration with configuration capacity sizes of 20, 12.64, 19.97, 11.66, and 13.45 MW, respectively. Finally, the system is operated according to the optimized energy storage configuration.

Compared with Scenario 1, both the operating cost and the power loss of the generator set are significantly reduced, and the operating cost and the pollution discharge are reduced. At the same time, the voltage of the photovoltaic and load bus is optimized, and the voltage is no longer down and overvoltage in the system. However, compared with Scenario 1, the system voltage deviation rate increases, indicating that the optimal power flow analysis method still has some defects.

Table 4. Simulation results for Scenario 2.

Wind power generation capacity (MW)	0	14.49	55.81	97.11	112.12
Probability (%)	6.79	20.39	40.46	19.88	12.30
Operating cost ($ / h)	12414	12277	11910	11572	11464
Voltage deviation	4.69	4.63	4.56	4.62	4.70
Emission (Kg / h)	225.98	224.22	218.2	205.75	199.85
Loss (MW)	4.62	4.75	5.34	5.75	5.94
Bus line 1 (MW)	117.70	114.98	106.51	94.68	89.63
Bus line 5 (MW)	13.91	10.78	0.80	0	0
Bus line 8 (MW)	3.55	0.98	0	0	0
Bus-line l1 (MW)	17.94	15.83	8.15	18.63	0
Bus-line l3 (MW)	57.20	53.32	39.78	12.64	8.99
Average operating cost ($ / h)	11898				
Average voltage deviation of (%)	4.61				
Average emission (Kg / h)	215.23				
Energy storage node configuration	Node 7 / 21 MW, node 19/12.59 MW, node 21/19.92 MW, node 24/11.63 MW, node 30/13.46 MW,				
Gross capacity	78.60 (MW)				

(3) Scenario 3: Intelligent algorithm that does not consider the constraints

For distributed wind power, the classical method can not be established, so an evolutionary algorithm should be adopted. In the algorithm, the bus voltage, generator output power, and storage capacity of all buses need to be assigned initial values according to boundary conditions. Then, the data is continuously updated as the algorithm is repeated. Finally, on some buses, the size of the storage space is equal to zero, which means that there is a new storage space on some buses and no ESS is needed, while the ESS capacity of other buses will converge to their own optimal value.

Single goal: Minimize operating cost. Compared with Scenarios 1 and 2, the operating cost, pollutant emission rate, and voltage deviation were significantly reduced in Scenario 3.

Double goal: minimize operating cost and minimize voltage deviation. Compared to Scenarios 1 and 2, both the pollutant emission rate and voltage deviation decreased in Scenario 3, but the running cost was lower than Scenario 1 and higher than Scenario 2. In addition, energy capacity is smaller than Scenario 2; but the energy storage configuration capacity scale increases slightly compared to the single target. As expected, the operating cost increases slightly, while the voltage bias decreases significantly.

Three objectives: minimize operation cost, minimize voltage deviation, and minimize pollutant emission. In this scenario, the TOPSIS is applied, the method analyzes the problem, and the specific simulation results are shown in the attached Table 5. Both the emission rate and voltage deviation of the pollutant were decreased compared to the previous two scenarios. The energy configuration is the smallest.

Table 5. Three-objective simulation results for Scenario 3.

Wind power generation capacity (MW)	0	14.49	55.81	97.11	112.12
Probability (%)	6.79	20.39	40.46	19.88	12.30
Bus line 1 (MW)	103.8	99.431	78.832	82.498	70.675
Bus line 5 (MW)	54.183	53.216	34.050	24.331	30.186
Bus line 8 (MW)	41.273	27.207	27.931	21.131	12.845
Bus-line 11 (MW)	43.201	46.420	44.069	28.277	27.99
Bus-line 13 (MW)	10.923	13.252	12.756	1.5672	1.1212
Operating cost ($ / h)	12579	12446	12052	11656	11568
Loss of power (MW)	3.13	3.12	3.49	4.96	4.89
Pollutant Discharge (Kg / h)	175.30	173.89	170.23	165	166.82
Voltage deviation (%)	0.246	0.182	0.380	0.385	0.396
Computation time (s)	601.56	563.48	605.84	558.49	604.88
Energy storage configuration	Node 7/11.10 MW, Node 19 / 10.50 MW, Node 30/11.30 MW,				
Average operating cost ($ / h)	12031				
Average voltage deviation of (%)	0.378				
Mean pollutant discharge (Kg / h)	170.41				
Energy storage capacity (MW)	31.98				

Detailed results for Scenario 3 are shown in Figures. 1a-1d. The operation cost, voltage deviation, pollutant emission, and solution time are compared and analyzed.

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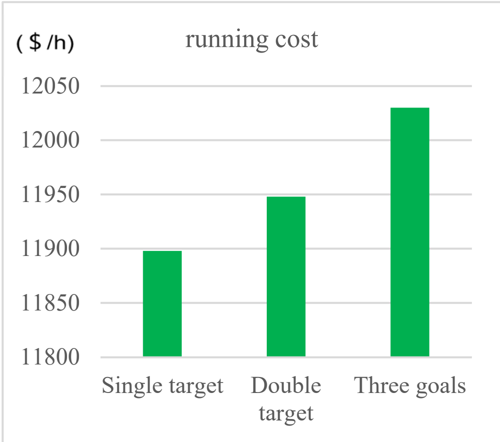
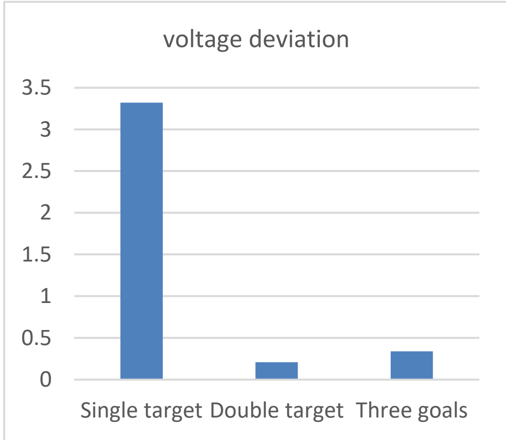
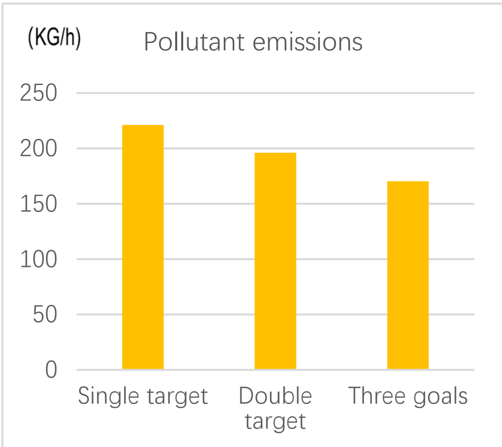


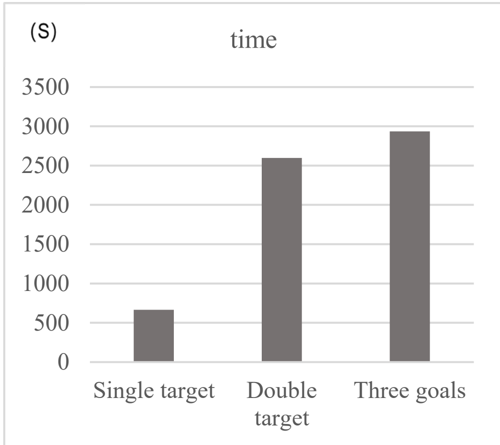
Graph 1a



Graph 1b



Graph 1c



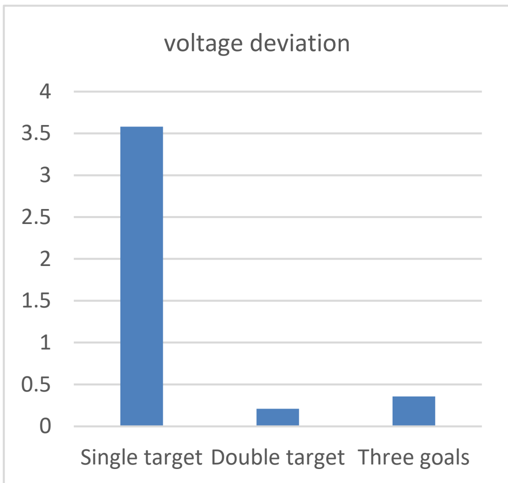
Graph 1d

Fig. 1. Scenario 3 Comparison of results under different target settings.

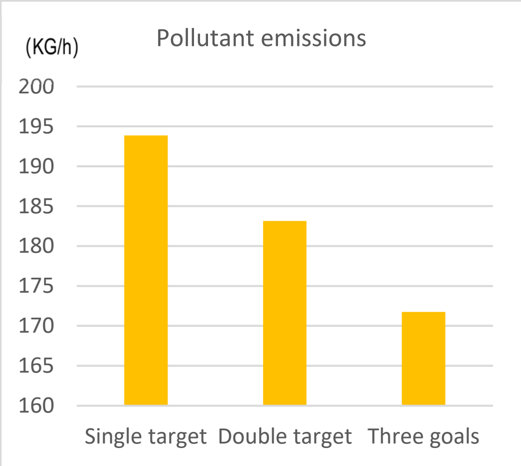
(4) Scenario 4: Optimization algorithm considering actual boundary conditions

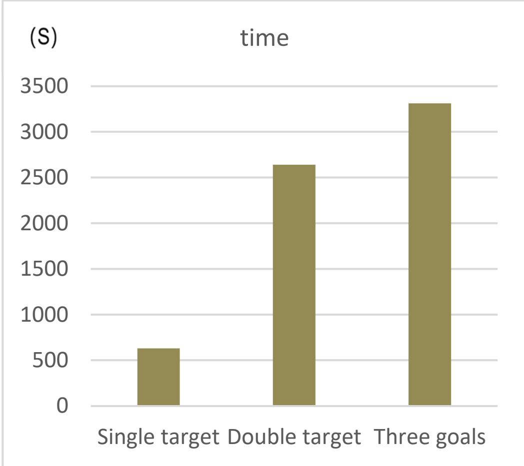
In this scenario, all boundary conditions are added, especially the forbidden zone and the minimum generation capacity of the unit, and the operating cost will increase. As shown in Figures 2a-2d.

Graph 2a



Graph 2b





Graph 2c Graph 2d

Fig. 2. Scenario 4 Comparison of results under different target settings.

Figure 2a shows the cost values for the three target scenarios. Figure 2b shows the voltage deviation under three target scenarios. Figure 2c shows pollutant emissions under three target scenarios. Figure 2d shows the calculation time under three target scenarios. Energy storage allocation price plays an important role in the cost of power systems, which leads to different energy and system configuration strategies. In addition, the price of energy storage devices is constantly changing, so different prices can lead to different operating costs and different sizes of energy storage configurations.

6. Conclusion

This paper presents an effective algorithm PLF-NSGAII-MOPSO to evaluate the optimal position of the energy storage system under wind power uncertainty. In addition, realistic constraints such as generating power constraints, forbidden area constraints, and ramp rate constraints affecting power system performance are considered in this regard. Moreover, the five-point estimation method is used to model the uncertainty of wind energy resources. Taking the IEEE30 node system as a case study network, the results show that the method proposed in this paper can find the appropriate location and capacity of energy storage configuration, minimize the total operating cost and pollutant emission, and improve the voltage distribution.

References

1. Liangzhong Yao, Zhanfeng Deng, Jianlin Li, Caiping Zhang, Progress in large-scale energy storage technology and its application in high proportion of renewable energy and power electronic equipment Global Energy Internet, **4 (05)**, 425-426 (2021)
2. Jian Liu, Economic analysis of energy storage technology adapted to the consumption of renewable energy, Energy Storage Science and Technology, **11 (1)**, 397-404 (2022)
3. Chaoping Wang, Haiying Liu, Qiancheng Bei, etc, Research on wind farm energy storage capacity optimization based on non-parametric estimation, Journal of Qilu University of Technology, **35 (4)**, 59-65 (2021)
4. Kai Wang, Yuan Zhang, Yanping Sun, et al, A distributed energy system based on wind energy storage, Steam Turbine Technology, **(5)**, 335-338+358 (2013).
5. Guoqing Liu, Research on multi-objective hybrid power flow optimization of electricity-gas regional integrated energy system, North China University of Water Resources and Electric Power, (2022)
6. Mingjie Park. Research on the unloading method of Internet of Vehicles task based on Mobile Edge Computing, Tianjin, Tianjin University of Technology, (2022)
7. Cisong, Yanglin Zhou, Hongjun Wang, et al, Case study of —— base station energy storage application of digital Energy Storage System modeling and operation control based on reconfigurable battery network, Global Energy Internet, **4 (5)**, 425-435 (2021)
8. Haixia Sun, Liwei Zhu, Yuqian Han, et al, Hybrid energy storage capacity configuration method of micro-grid based on non-cooperative game, Global Energy Internet, **4 (5)**, 454-463 (2021)
9. Jia Liu, Yisheng Liu, Ying Shi, Study on the optimization method of construction project duration-cost-quality balance based on fuzzy set theory, Journal of Beijing Jiaotong University, **16 (3)**, 30-38 (2017)
10. Tingting Hou. Research on the optimal configuration of energy storage power supply in power system with large-scale wind power, Huazhong University of Science and Technology (2024)

11. C. Liang, W. Xiong, H. Wang, et al, Identification and maximum impact force modeling investigation for critical slugging in underwater compressed gas energy storage systems, Journal of Energy Storage (2023)
12. A Suvorov, A Askarov, V Rudnik, et al, A novel approach to validation of a positive-sequence modeling of a converter-interfaced generation with hydrogen energy storage in practical power systems, International journal of hydrogen energy, (2023)
13. R. N. Kouchesfahani, S. S. Mohtavipour, H. Mojallali. Simultaneous Network Reconfiguration and Wind Power Plants Participation in Day-Ahead Electricity Market Considering Uncertainties, Energy Technology, Generation, Conversion, Storage, Distribution, **9**,11 (2023)