Optimization of Energy Storage Capacity to Smooth Wind Power Fluctuation

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Abstract. The uncertainty and randomness of wind power generation bring hidden trouble to the safe operation of power distribution network. Combining energy storage system with wind power generation can effectively improve the output characteristics of wind power generation. In this paper, considering the investment cost of energy storage and the effect of suppressing the fluctuation of wind power output, the optimization of energy storage capacity under the scenario of wind power grid connection is studied. Firstly, the multi-objective capacity optimization model of the energy storage system is established to minimize the cost of the energy storage system and the variance of wind power system output equipped with energy storage. Then, the multi-objective optimization problem is transformed into a single objective optimization problem by introducing the weight coefficient of the objective function and the particle swarm optimization algorithm (PSO) is used to solve the problem. Finally, through the test of IEEE-33 bus distribution network system, the relationship curve between energy storage capacity and wind power fluctuation suppression effect is obtained. The results of numerical examples show the effectiveness of the proposed method.

1. Introduction

In the power distribution network, distributed energy represented by wind power and solar power generation plays a positive role in reducing pollution and power loss, but the fluctuation of its output is bound to affect the safe operation of the distribution network [1]. Energy Storage System (ESS) can quickly regulate power, absorb or release excess electric Energy, realize the time shift of electric Energy, which suppress the output fluctuation of distributed generation effectively [2-3]. It can be combined with distributed generation to form a complete system to improve the stability of distributed generation output [4].

At present, the energy storage system has been applied successfully in many aspects, such as suppressing fluctuations, and improving new energy utilization rate [5]. Based on the spectrum analysis of new energy output, [6]-[7] proposed the operation strategy of using energy storage batteries to suppress the short-term fluctuation of new energy output and the evaluation method of the optimal capacity of energy storage batteries. [8] combines spectrum analysis with low-pass filtering to
determine the optimal energy storage capacity configuration to meet the smooth output operation control requirements. [9] aims to improve the net profit of optical storage system, and builds an investment return model of optical storage system considering the economy of users on the distribution side, providing a strong basis for the energy storage configuration of users on the distribution side.

In this paper, considering the construction and operation costs of energy storage and the effect of suppressing wind power fluctuations, a multi-objective optimal configuration model of the energy storage system and its solution method are proposed. The wind generator with known output curve is optimized to achieve the comprehensive optimization of energy storage costs and suppressing wind power fluctuations.

2. Optimization model of energy storage capacity

2.1. Objective function

The model has two objective functions, one is the minimum construction and operation costs of energy storage system, the other is the minimum variance of wind power output fluctuation with energy storage.

As the initial investment of energy storage is large, all the costs of energy storage are converted into one-year period for calculation, and the objective function is as follows:

$$\min F_{\text{total}} = f_1 - f_2 - f_3$$

Where $f_1$ is the construction investment costs of energy storage, $f_2$ is the benefits obtained by energy storage in the process of storing electric energy at low electricity prices and releasing electric energy at high electricity prices, $f_3$ is the reduced network loss costs of the distribution network after the energy storage is equipped with.

$$f_1 = \alpha \left( c_p P_{\text{ess}} + c_e E_{\text{ess}} \right) \frac{\tau (1+\tau)^y}{(1+\tau)^y - 1} \left( c_p P_{\text{ess}} + c_e E_{\text{ess}} \right)$$

Where $\alpha$ is the discount factor that converts it into annual investment cost which annualizes the investment cost of the energy storage system over the service life. $\tau$ stands for annual interest rate, and $y$ stands for the service life of the energy storage device. $c_p$ and $c_e$ are the construction costs of energy storage per unit power and per unit capacity. $P_{\text{ess}}$ and $E_{\text{ess}}$ are the power capacity and energy capacity of energy storage.

Taking into account the output characteristics of wind power, energy storage system generally stores electric energy during the peak period of wind power, when the price of electricity is lower, and releases electric energy during the low period of wind power, when the price of electricity is higher. In this process, the energy storage system will generate revenue due to the existence of price difference.

$$f_2 = n \sum_{t} e(t) P_{\text{ess}}(t) \Delta t$$

Where $P_{\text{ess}}(t)$ is the output of energy storage at time t, when $P_{\text{ess}}(t) > 0$ represents the energy storage system absorbs electrical energy, $P_{\text{ess}}(t) < 0$ represents energy storage system releases electrical energy. $e(t)$ represents the electricity price at time t, $T$ represents The number of time periods in a typical day, $\Delta t$ represents the length of the time period; $n$ is the total number of days in a year.

After equipped with energy storage, the annual network loss cost saved by the system is:

$$f_3 = n \sum_{t} e(t) \left( \Delta P^+(t) - P^+(t) \right) \Delta t$$

Where $\Delta P^+(t)$ and $\Delta P^-(t)$ are the network loss of the system at time t before and after energy storage system equipped with.

Taking the fluctuation variance of wind power output smoothed by the energy storage device as the measure of the effect of energy storage on suppressing wind power fluctuations, the objective function is expressed as:
\[
\min F_{fu} = \sum_t \left( P_{WT}(t) + P_{ess}(t) - P_{ave} \right)^2
\]  
(5)

Where \( P_{WT}(t) \) is the output power of wind power at time \( t \), \( P_{ave} \) is the average value of the output power of wind power smoothed by the energy storage device, which can be expressed as:

\[
P_{ave} = \frac{1}{T} \sum_t \left( P_{WT}(t) + P_{ess}(t) \right)
\]  
(6)

2.2. Constraints

1) Node power balance constraint

For a power grid with \( N \) buses, bus power balance need to be satisfied:

\[
P_i(U, \theta) = U_i \sum_j U_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right)
\]  
(7)

\[
Q_i(U, \theta) = U_i \sum_j U_j \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right)
\]  
(8)

2) Node voltage constraint

\[0.95 \leq U_i \leq 1.05\]  
(9)

3) Storage energy charging and discharging power constraint

\[P_{ess\_min} \leq P_{ess}(t) \leq P_{ess\_max}\]  
(10)

Where \( P_{ess\_min} \) and \( P_{ess\_max} \) are the upper limit constraint of the discharge power and the upper limit constraint of the charging power of the energy storage system respectively.

4) Energy storage system energy balance constraint

In order to better describe the energy at each moment of energy storage system, the variable \( s(t) \) is introduced:

\[s(t) = -\sum \eta P_{ess}(t) \Delta t\]  
(11)

Where \( \eta \) is the conversion coefficient of energy storage charge and discharge efficiency, as shown in equation (12):

\[
\eta = \begin{cases} 
\frac{1}{\eta_d} & (P_{ess}(t) > 0) \\
\eta_c & (P_{ess}(t) < 0) 
\end{cases}
\]  
(12)

Where \( \eta_d \) and \( \eta_c \) are the discharge efficiency and charging efficiency of the energy storage system respectively. In order to ensure the continuous operation of the energy storage system, the energy of charging and discharging within a cycle should conform to the conservation of energy.

\[s(T) = 0\]  
(13)

5) Energy storage system power capacity and energy capacity constraints

The power capacity and energy capacity of the energy storage system are determined according to the output and energy at each time of the energy storage.

\[P_{ess} = K_p \max (P_{ess}(t))\]  
(14)

\[E_{ess} = K_e (\max(s(t)) - \min(s(t)))\]  
(15)

Where \( K_p \) and \( K_e \) are the safety margins of energy storage system power capacity and energy capacity respectively.

3. Optimization model solution

The optimal allocation model of energy storage capacity is a multi-objective problem, and the two objectives restrict each other. In order to simplify the calculation process, this paper transforms the multi-objective problem into a single-objective problem by introducing the weight coefficient of the
objective function, as shown in equation (16), and then uses the particle swarm optimization algorithm (PSO) to solve it.

$$\min F = F_{\text{total}} + \lambda F_{\text{flu}}$$ (16)

Where $\lambda$ is a weight coefficient that makes the two objective function values at the same magnitude. By changing the size of $\lambda$, the importance of the two objective functions $F_{\text{total}}$ and $F_{\text{flu}}$ in a single objective function $F$ can be changed.

When using the PSO to optimize the capacity of energy storage, the output of energy storage system needs to be coded. The coding form is:

$$x = [x_1, x_2, \ldots, x_i, \ldots, x_T]$$ (17)

Where $x_i$ is the output value of the energy storage system at time $t$. Use PSO to solve this problem. In the iterative process, the individual particle code $x$ is continuously updated according to the group optimal solution and the individual optimal solution. Finally, the individual particle code that minimizes the objective function $F$ is found, and then the value of each objective function and the power capacity and energy capacity of the energy storage system are obtained. The basic steps of solving this problem based on PSO are as follows:

1. Initialization. Enter the original data of the distribution network, and randomly generate the position and velocity of the particles, the learning factor, the inertia coefficient, and the maximum number of iterations within the constraints.
2. According to the position of the particle swarm and the data of the distribution network, MATPOWER is called to calculate the power flow of the distribution network to obtain the network loss before and after the energy storage is added, and calculate the fitness value of the particles that meet the constraints.
3. According to the fitness of each particle, calculate the individual optimal solution and the group optimal solution of the particle.
4. Update the speed and position of each particle according to the individual optimal solution and the group optimal solution according to equations (18) and (19). Then determine whether the convergence condition is reached, if not, turn to (2), otherwise turn to (5).
5. Output the optimal solution of the population, calculate the value of each objective function and the result of energy storage configuration.

$$v_{i}^{k+1} = \omega(k)v_{i}^{k} + c_1r_1(p - x_{i}^{k}) + c_2r_2(g - x_{i}^{k})$$ (18)

$$x_{i}^{k+1} = x_{i}^{k} + v_{i}^{k+1}$$ (19)

$$\omega(k) = (\omega_{\text{ini}} - \omega_{\text{end}})\frac{K - k}{K} + \omega_{\text{end}}$$ (20)

Where $k$ is the current number of iterations, $K$ is the maximum number of iterations; $x_{i}^{k}$ is the particle position variable; $v_{i}^{k}$ is the variable of particle velocity; $p$ and $g$ are individual optimal solution and group optimal solution respectively; $c_1$ and $c_2$ are individual learning factor and group learning factor respectively; $r_1$ and $r_2$ are the random number on the interval $[0,1]$; $\omega_{\text{ini}}$ and $\omega_{\text{end}}$ is the initial inertia weight and the end inertia weight respectively, and $\omega(k)$ is the inertia weight of the $k$-th iteration. Formulas (18) (19) and (20) are the calculation formulas of individual velocity of particle swarm, individual position of particle swarm and inertia weight of particle swarm respectively.

### 4. Case analysis

In order to verify the effectiveness of the proposed model, this paper selects the revised IEEE-33 buses distribution network for analysis, and the structure of the system is shown in Figure 1. The reference voltage of the distribution network is 12.66kV, and the total load is 3.715+j2.3MW. A wind turbine with a rated power of 600kW is added at bus 9, and an energy storage system is installed at bus 9 where the wind turbine is located. The bus where wind power and energy storage are located are treated as PQ bus, and the energy storage capacity is optimized using the method proposed in this paper. The wind power output curve and load curve of the system in a typical day are shown in Fig 2.
This paper adopts the time-of-use electricity price. The electricity price during peak hours from 09:00 to 22:00 is 0.2$/\text{(kW} \cdot \text{h})$ and the electricity price during the rest of the period is 0.1$/\text{(kW} \cdot \text{h})$; the investment cost and other parameters of the energy storage system are as shown in Table 1.

### Table 1. Case analysis parameters.

| Parameters       | Value | Parameters       | Value |
|------------------|-------|------------------|-------|
| $c_p$/[$\text{S} \cdot (\text{kW} \cdot \text{h})^{-1}$] | 400   | $\eta_d$/%       | 95    |
| $c_e$/[$\text{S} \cdot (\text{kW})^{-1}$]         | 150   | $\eta_c$/%       | 95    |
| $\tau$/%         | 10    | $\Delta t$/h     | 1     |
| $y$/a            | 15    | $T$              | 24    |
| $P_{ess,max}$/kW  | 80    | $K_p$            | 1.2   |
| $P_{ess,min}$/kW  | 80    |                  | 1.2   |

In order to quantitatively analyse the fluctuation of wind power output after with energy storage equipped, the fluctuation ratio $f$ is defined as the ratio of the variance of wind power output fluctuation before and after energy storage equipped with:

$$f = \frac{\frac{1}{T} \sum_{t=1}^{T} (P_{WT}(t) + P_{ess}(t) - P_{ave})^2}{\frac{1}{T} \sum_{t=1}^{T} (P_{WT}(t) - P_{WTave})^2} \times 100\%$$  \hspace{1cm} (21)

Where $P_{WTave}$ is the average output of wind power:

$$P_{WTave} = \frac{1}{T} \sum_{t=1}^{T} P_{WT}(t)$$  \hspace{1cm} (22)

Set the weight coefficient $\lambda=0.5$ and use the method proposed in this paper to optimize the energy storage capacity. The optimization results are shown in Table 2. The output curve of wind power generation with and without energy storage system and the energy storage system charge and discharge curve are shown in Figure 3.
Table 2. Energy storage optimization results.

| Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|
| $P_{ess}$/kW | 80    | $f_1$/\$/h | 15160 |
| $E_{ess}$/kW·h | 625   | $f_2$/\$/h | 1992  |
| $F_{total}$/\$/h | 17623 | $f_{flu}$/h | 26870 |
| $f_3$/\$/h | 34775 |

It can be seen from Table 2 that by allocating 80kW and 625 kW·h energy storage system for wind power generation, the fluctuation of wind power output can be significantly reduced to 18.62% of the original. The annual investment cost of energy storage system $f_1$ is $34775. The arbitrage of energy storage system $f_2$ is $15160. After equipped with energy storage system, the network loss cost saved in one year $f_3$ is $1992. The total cost of energy storage system in one year $F_{total}$ is $17623.

Figure 3. Wind power output curve and energy storage charge and discharge curve.

Figure 4. Total cost and volatility ratio under different weight coefficients.

In Fig 3, the curve of electric energy variation of energy storage system describes the change of electricity quantity of energy storage system from 0 hours to sampling time in a typical day. It can be seen from Figure 4 that the energy storage system is charged during the peak period of wind power output from 0:00 to 7:00, and the maximum charging capacity reaches 463kW·h. During the low period of wind power output from 9:00 to 17:00, the maximum discharge capacity reaches 58kW·h. In a complete cycle, the energy storage system is charged equal to the discharge capacity, so the energy storage system can operate continuously.

Changing the weight coefficient $\lambda$ can change the importance of the objective functions $F_{total}$ and $F_{flu}$, thereby obtaining different optimization results. Fig 4 shows the quantitative relationship between the total cost $F_{total}$ and the fluctuation ratio $f$ under different $\lambda$, which values range from 0.1 to 1 with an interval of 0.1.
It can be seen from Fig 4 that as $\lambda$ increases, the proportion of $F_{\text{flu}}$ in $F$ gradually increases, and the optimized energy storage investment cost $F_{\text{total}}$ increases while the fluctuation variance of wind power output with energy storage gradually decreases. By introducing the objective function weight coefficient $\lambda$, the multi-objective optimization is transformed into a single-objective optimization problem, which simplifies the difficulty of calculation. But by assigning different values of $\lambda$, an approximate Pareto Curve can be obtained. Provide a flexible reference solution for energy storage capacity optimization under different scenarios.

5. Conclusions
The paper comprehensively considers the economy of energy storage system and its ability to smooth wind power fluctuations, and a multi-objective optimal allocation model of energy storage system is proposed with the objective of minimizing the annual construction and operation cost of energy storage system and minimizing the fluctuation variance of wind power output after energy storage system. By introducing the weight coefficient of objective function, the multi-objective problem is transformed into a single objective problem. PSO algorithm is applied to solve the problem, and the optimal energy storage allocation scheme with different weight coefficients is obtained.

The case analysis shows that the proposed optimal allocation model and solution method can effectively reduce the fluctuation of wind power output while control the energy storage cost. The energy storage allocation scheme is reasonable, efficient and practical which significantly reduce the fluctuation of wind power output.

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