Smoothing Control Strategy of Wind Power Based on Adaptive Adjustment of Fluctuation Coefficient

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Abstract. Due to the strong randomness and fluctuation of wind power, a direct access to the power grid will be an adverse effect on the quality of the power. The energy storage system can not only reduce the phenomenon of abandoned wind power, but also improve the quality of the power grid. In order to smooth the fluctuation of wind power, we propose a smooth control strategy of wind power based on adaptive adjustment of fluctuation coefficient. The optimal model is designed which is based on minimize the energy storage capacity. The method of sliding window and particle swarm optimization (PSO) is used to solve the problem. The wind power grid-connected power value is obtained.

1. Introduction
With the rapid development of wind power technology, the total installed capacity of wind farms continues to increase, and the wind power penetration rate is also increasing. In order to improve the grid-connecting capacity of wind power and reduce the phenomenon of wind curtailment, it is possible to equip wind farms with a certain capacity of energy storage system[1]-[2].

How to use less energy storage capacity to stabilize the wind power fluctuations during wind power grid connection and it put forward higher requirements for control systems. In the research of control algorithms, more and more control algorithms have been proposed. The first-order low-pass filtering algorithm is widely used because of its simple principle and fast calculation speed[3]-[5]. However, it has a certain delay in tracking wind power changes. In[6], only the particle swarm optimization (PSO) algorithm is considered, and the overall data impact on the grid-connected wind power is not considered when the particle swarm is trapped in the local optimal solution. In [7]-[8], a fuzzy control strategy is proposed to stabilize the wind power through 'state of charging (SOC) changes. In[9], Using the empirical mode decomposition method to quickly analyze the wind power fluctuations, we obtain the energy storage stabilization control command. Based on the above research, this paper considers the smoothing effect of wind power grid connection and the reduction of energy fluctuations. Considering the actual situation, a control algorithm based on adaptive adjustment of fluctuation coefficient is designed.

2. Wind power smoothing strategy
At present, the energy storage system has different configurations according to the actual situation of the wind farm. There are mainly two structures: distributed and centralized. The distributed wind farm energy storage system is equipped with a small capacity energy storage device for each fan in the wind
farm. And the centralized wind farm energy storage system is equipped with a large capacity energy storage device for the entire wind farm. This paper selects the centralized wind farm energy storage system for analysis.

2.1 Proposal of Wind Power Smoothing Strategy

The energy storage system needs to timely absorb or release the difference between the wind power and the grid-connected power, and improving the power quality of the power grid. Energy balance on the centralized wind energy storage system:

\[ P_{\text{tot}}(t) = P_{\text{ess}}(t) + P_{\text{w}}(t) \]

Where, \( P_{\text{ess}}(t) \) is the power absorbed or released by energy storage. \( P_{\text{w}}(t) \) is the total wind power of selected fans for time \( t \). \( P_{\text{tot}}(t) > 0 \) is that the energy storage system is charging. \( P_{\text{tot}}(t) < 0 \) is that the energy storage system is discharging.

The slope of the wind power curve directly reflects the fluctuation of power. The greater the slope at the moment of \( t \sim (t + \Delta t) \), the greater the change rate of power and the more obvious the fluctuation. Thus the wind power integration can be obtained, as shown in formula (2).

\[
\frac{P_o(t + \Delta t) - P_o(t)}{\Delta t} = W_j \times \frac{P_w(t + \Delta t) - P_w(t)}{\Delta t} + W_j \times P_w(t)
\]

Where, \( t \) is the current time and \( \Delta t \) represents the step size. \( W_j \) is the fluctuation coefficient. It can be known that the smaller the fluctuation coefficient, the better smoothing effect on the wind power and the more stable the grid-connected power of the wind farm. However, this may lead to excessive repression.

2.2 Wind power fluctuation definition

When wind power is connected to the power grid, the fluctuation of its active power is the main consideration of this paper. The sampling time is one minute. Define the fluctuation ratio of wind power integration within one minute:

\[ \Delta P_{o,1\text{min}} \% = \left| \frac{P_{o,1\text{min}} - P_{o,t-1}}{P_r} \right| \]

Where, \( P_{o,t} \) is the grid-connected power for time \( t \). \( P_{o,t-1} \) is the grid power of the previous moment. \( P_r \) is wind farm rated power.

Define the fluctuation ratio of wind power grid connected within ten minutes:

\[ \Delta P_{o,10\text{min}} \% = \left| \frac{\max(P_{o,10\text{min}}) - \min(P_{o,10\text{min}})}{P_r} \right| \]

Where, \( \max(P_{o,10\text{min}}) \) is the maximum value of grid-connected power in ten minutes. \( \min(P_{o,10\text{min}}) \) is the minimum value of grid-connected power in ten minutes.

From the definition of wind power fluctuation rate of ten minutes, the power fluctuation of ten minutes is accumulated by the power fluctuation of one minute. The wind power fluctuation constraint of one minute in the wind power grid connection should be considered first, and then the wind power fluctuation of ten minutes is considered. According to China’s "Technical Rule for Connecting Wind Farm to Power System", if wind power is to be connected to the grid, the change rate of wind farm output power must be limited. Table 1 is the technical regulations for wind power fluctuations in China[10].

| Wind farm installation capacity /MW | Ten minutes active power change maximum limit /MW | One minute active power change maximum limit /MW |
|-----------------------------------|-----------------------------------------------|-----------------------------------------------|
| <30                               | 10                                            | 3                                             |

Table 1. Maximum variation of active power in wind farm
3 Particle Swarm Optimization Algorithm Based on Sliding Window

For the economic analysis of engineering applications, it is necessary to minimize the size of the energy storage system to reduce the cost of the wind farm energy storage system. The particle swarm modeling parameter of the sliding window selects the fluctuation coefficient $w_i$ in equation (2). In this paper, eight 1.5 MW units of a centralized wind farm were selected and analyzed using the collected one minute fan power data. The particle swarm optimization algorithm is used to optimize the fluctuation coefficient. The output of the model is the power absorbed or released by the energy storage system. Because the particle group is easy to fall into the local optimum, it has a great influence on the output. On this basis, we introduce the concept of sliding window to eliminate the impact of particle swarming into local optimum on the overall data of energy storage system. Usually the price of an energy storage system is proportional to the size of its energy storage capacity, so minimizing the capacity of the energy storage system is an objective function [11]. Define the objective function as:

$$F = \min \left[ \frac{1}{n} \sum_{i=1}^{n} [P_{o,s}(w_i) - P_{o,f}]^2 \right]$$

(5)

Where, $F$ is the smallest energy storage capacity. $n$ is sampling points in the time scale. $P_{o,s}(w_i)$ is the target power after the smoothing of the fluctuation coefficient for time $t_i$. The constraints are:

1. The fluctuations per minute are less than 2% of the rated power of the system.
2. The fluctuations every ten minutes are less than 20% of the rated power of the system.

$$\begin{cases} \Delta P_{o,1\text{min}} \% \leq k_1 \\ \Delta P_{o,10\text{min}} \% \leq k_2 \end{cases}$$

(6)

Where, $\Delta P_{o,1\text{min}} \%$ is the volatility within one minute. $\Delta P_{o,10\text{min}} \%$ is the volatility within ten minutes. $k_1$ and $k_2$ is Maximum power fluctuation.

In order to avoid the excessive constraints in the optimization process and avoid the influence of the defects of the PSO algorithm on the overall data of the energy storage system, we use the sliding window method (Figure 2) to dynamically optimize the fluctuation coefficient. We can rewrite equation (5) as:

$$P = \min \left[ \frac{1}{N_t} \sum_{j=1}^{N_t} [P_{o,s}(w'_j) - P_{o,f}]^2 \right]$$

$$F = \frac{1}{n} \sum_{i=1}^{n} [P_{o,s}(w'_i) - P_{o,f}]$$

(7)

Where, $P$ is the smallest energy storage capacity in the set sliding window width. $N_t$ is sliding window width. $P_{o,s}(w'_j)$ is the target power obtained after the smoothing of the optimal fluctuation coefficient obtained in the sliding window. $F$ is the smallest energy storage capacity in the total sampling point $n$ of the system.

Since the system needs to meet the wind power grid-connected power fluctuation requirements, here we set the sliding window width $N_t$ to 10.

Obtain continuous $N_t-1$ wind power data before $t$ time and $t$ time. Establish an optimization model equations (2) and (7) with the variable $w_i$. The constraint is equation (6). The PSO algorithm...
is used to obtain the optimal fluctuation coefficient \( w'_t \), which is used as the fluctuation coefficient at time \( t \), so as to obtain the minimum compensation power of the energy storage system.

\[
\text{Window 1} \quad \text{Window 2} \quad \text{Window 3} \\
\begin{array}{c}
1 \\
2 \\
3 \\
\vdots \\
N
\end{array}
\begin{array}{c}
N+1 \\
N+2 \\
\vdots \\
\end{array}
\text{Time series}
\]

\textbf{Figure 1.} Flow chart of particle swarm algorithm based on sliding window

\textbf{Figure 2.} Slide window diagram

4 Energy storage device capacity calculation

The battery is widely used in all walks of life. It has the advantages of stable voltage, high safety and flexible energy storage capacity. Based on the above advantages, this paper uses the battery as an energy storage unit to stabilize wind power fluctuations [12]-[13].

4.1 Rated power

Considering the charging and discharging efficiency of the system:

\[
P_{\text{ess},t} = \begin{cases} 
    P_{\text{ess},t} / m_1, & P_{\text{ess},t} > 0 \\
    P_{\text{ess},t} / m_2, & P_{\text{ess},t} < 0 
\end{cases}, \quad t = 1, 2, \ldots, n
\]

(8)

Where, \( P_{\text{ess},t} \) is the storage energy power compensation at time \( t \). \( m_1 \) is the charging efficiency of energy storage battery. \( m_2 \) is the discharge efficiency of energy storage battery. \( n \) is the sample points.

During the entire sampling period, the rated power of energy storage is defined as the maximum absolute value of the power compensation required by the energy storage system:

\[
P_e = \max \left\{ \left| P_{\text{ess},t} \right| \right\}
\]

(9)

4.2 Nominal capacity

Charge and discharge of energy storage at different times relative to the initial time:

\[
E(t) = E(0) + \sum_{t=0}^{n} P_{\text{ess},t}, t = 1, 2, \ldots, n
\]

(10)

Where, \( t \) is the sampling interval, \( n \) is the number of sampling points. \( E(0) \) is the initial energy of the energy storage battery. Here we assume that the initial energy is 0 for simplicity.

In practical applications, energy storage devices generally have problems of overcharging and overdischarging. Overcharge and overdischarge will affect the life of the energy storage system. Therefore, the battery will have a certain working range, and state of charging (SOC) is usually between 0.2 and 0.8. The required rated capacity of the battery:

\[
C = (\max_{t=1-n} | E(t) |) / 0.5
\]

(11)
5 Examples Analysis

The actual output power of a certain wind farm is analyzed in China in 2015. As shown in the flowchart of Figure 1, the control strategy combining sliding window with PSO is used to solve the problem.

The actual output grid-connected power of the wind farm is obtained by this paper’s algorithm and the first-order low-pass filter algorithm as shown in Figure 3. By comparison, it can be found that the wind power grid-connected power is smoothed by the control algorithm of this paper, which can reduce the wind power fluctuation and make the power curve smoother. The local data of the wind farm in Figure 3 is selected for analysis. As shown in Figure 4.

![Figure 3. Comparison of wind power smoothing effect at 1440 min](image)

![Figure 4. Comparison of wind power smoothing effect at 60 min](image)

Figure 5 and Figure 6 are the power fluctuations of one minute and ten minutes for grid-connected power in Figure 3. It can be found that the volatility of the particle swarm optimization algorithm based on sliding window is significantly lower than that of the first-order low-pass filtering algorithm. The feasibility and effectiveness of the control strategy in this paper are verified.

![Figure 5. Comparison of wind power fluctuation rate of one minute](image)

![Figure 6. Comparison of wind power fluctuation rate of ten minutes](image)

The parameters of fixed fluctuation coefficient and the algorithm are compared in Table 2. In order to make the wind power grid-connected power meet the fluctuation requirements of one minute and ten minutes, when the fixed fluctuation coefficient is 0.1, the fluctuation requirements of the two time scales are basically satisfied. The required rated power is 2.5501 MW and the required capacity is 3.1192 MW.h. By using the algorithm presented in this paper, the required power rating is 2.2347 MW and the required capacity of the required configuration is 2.3359 MW.h. Although the volatility increased slightly in ten minutes, it fully meets the wind power grid connection requirements.
Compared with the fixed fluctuation coefficient, the control strategy of the algorithm in this paper greatly reduces the charging and discharging amount of the energy storage device during sampling time, reduces the energy storage capacity of the energy storage device, increases the use time of the energy storage device, and reduces the initial cost and maintenance cost of the system.

Table 2. Comparison of fixed fluctuation coefficient

| Fluctuation coefficient | Total charge and discharge (MW) | Rated power (MW) | Rated capacity (MW.h) | One minute maximum volatility | Ten minutes maximum volatility |
|-------------------------|-------------------------------|-----------------|-----------------------|-------------------------------|-------------------------------|
| 0                       | 43.6344                       | 4.7462          | 70.6925               | 0                             | 0                             |
| 0.1                     | 10.5407                       | 2.5501          | 3.1192                | 2.1%                          | 12.4%                         |
| 0.2                     | 7.6370                        | 1.6323          | 1.7401                | 3.4%                          | 18.9%                         |
| 0.3                     | 6.3499                        | 1.5389          | 1.5389                | 4.9%                          | 23.2%                         |
| 0.4                     | 5.3152                        | 1.1786          | 1.4731                | 6.5%                          | 26.1%                         |
| 0.5                     | 4.3755                        | 0.9765          | 1.3754                | 8.2%                          | 28.3%                         |
| 0.6                     | 3.4985                        | 0.7772          | 1.3340                | 9.7%                          | 29.5%                         |
| 0.7                     | 2.6423                        | 0.5770          | 1.3043                | 11.2%                         | 30.2%                         |
| 0.8                     | 1.7853                        | 0.3773          | 1.2818                | 12.6%                         | 30.6%                         |
| 0.9                     | 0.9083                        | 0.1830          | 1.2642                | 13.7%                         | 30.9%                         |
| 1                       | 0                             | 0               | 0                     | 14.9%                         | 31.1%                         |
| Algorithm               | 9.5144                        | 2.2347          | 2.3359                | 2.0%                          | 18.6%                         |

6 Conclusion
Based on the study of the smooth wind power fluctuation of energy storage system, this paper proposes a wind power smoothing strategy based on adaptive adjustment of fluctuation coefficient. The simulation analysis of the actual wind farm data is used to verify the feasibility of the method.

(1) Particle swarm optimization algorithm based on sliding window can further improve the wind power smoothing effect. In comparison with the first-order low-pass filtering algorithm, we can find that the fluctuation of the grid-connection power of one minute and ten minutes has been significantly reduced.

(2) The fluctuation coefficient is optimized by the particle swarm algorithm of sliding window, so that the fluctuation coefficient is adjusted adaptively. In the case that the wind power grid-connected fluctuation is satisfied, compared with the fixed fluctuation coefficient, the total amount of energy storage charge-discharge during the controlling is reduced, so as to reduce the number of charge-discharge times of the energy storage system in the wind power grid-connected process, which is helpful to extend the life of the energy storage device and reduce the storage capacity of the system and the cost of system.

This control strategy can not only process historical data, obtain small energy storage capacity and reduce system cost, but also stabilize the grid-connected wind power, so as to reduce the phenomenon of ‘abandoned wind power’. In the follow-up work, further consideration should be given to the control mode of energy storage system in order to achieve better wind level suppression effect.

7 References
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