Research on voltage control strategy optimization of wind farm cluster

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Abstract. With the continuous expansion of the grid-connected scale of wind farms, the problem of the stability of the grid-connected point voltage of wind farm cluster has become increasingly prominent. However, the current reactive voltage control strategy of wind farm cluster has less research on the optimization of the internal node voltage and grid loss of wind farms, and the problem of the reduction of wind turbine life caused by the full reactive power of doubly-fed wind turbines needs further research. In view of the above problems, this paper proposes a wind farm cluster reactive voltage hierarchical control strategy based on the reactive power margin of doubly-fed wind turbines. The strategy improves the traditional artificial fish algorithm and realizes the reactive voltage control of wind farm cluster. As a result, the node and network loss have reached a certain degree of optimization.

Keywords: Wind farm cluster, reactive power and voltage control, reactive power margin, SAAFSA.

1. Reactive voltage hierarchical control strategy and modeling of reactive voltage based on reactive power margin

1.1. Reactive voltage hierarchical control strategy based on reactive power margin

The reactive voltage hierarchical control strategy of doubly-fed wind farm cluster aims to maintain the voltage stability at the grid connection point of wind farm cluster [1]. The reactive voltage control is carried out by using the reactive power regulation ability and reactive power compensation equipment in wind farm cluster [2]. The reactive voltage hierarchical control strategy of doubly-fed wind farm cluster is shown in Figure 1. This control strategy is divided into three layers: agminate field layer, interstitial field layer and inner field layer. In the agminate field layer, according to the voltage and reactive power regulation of the grid connected point in the last wind farm cluster reactive voltage control, calculating the reactive power regulation required by the wind farm cluster at the current time [3]. In the interstitial field layer, distributing the reactive power regulation obtained from the agminate field layer among the single fields, and the reactive power margin of single field is considered in distribution [4]. In the inner field layer, taking the network loss, node voltage and reactive power...
margin of wind turbine in single field as optimization objective functions. Then optimizing the single field, the reactive power obtained from the interstitial field layer is distributed to the wind turbines and compensation equipments in a single field [5].

![Figure 1. Reactive voltage hierarchical control strategy of wind farm cluster based on reactive power margin](image)

1.2. Reactive voltage hierarchical control modeling based on reactive power margin

1.2.1. Objective function

1) Voltage requirements

The node voltage of each single field in the wind farm cluster should meet the requirements, and its objective function is

\[ F_1 = \min \sum_{j=1}^{m} (U_{jref} - U_j)^2 \]  

Where: \( m \) is the number of nodes in a single field, \( U_{jref} \) and \( U_j \) are the reference voltage and current voltage of each node in the single field.

2) Minimum network loss

In order to ensure the economy of wind farm cluster operation, the objective function of single field network loss is defined as

\[ F_2 = \min P_{loss} \]  

\[ P_{loss} = \sum_{j,k,m} G_{jk} [U_j^2 + U_j^2 - 2U_jU_k \cos \theta_{jk}] \]  

Where: \( P_{loss} \) is the network loss of wind farm.

3) Margin requirements

The reactive power margin of each single field in the wind farm cluster should meet the requirements, and its objective function is
\[ F_3 = \min \left[ Q_{\text{max}} - \sum_{j=1}^{n} (Q_{j_{\text{max}}} - Q_{j}) \right] \]  

(4)

Where: \( Q_{\text{max}} \) is the maximum value of reactive power generated by wind turbine.

To sum up, the total objective function of wind farm cluster is defined as

\[ F = \lambda_1 F_1 + \lambda_2 F_2 + \lambda_3 F_3 \]  

(5)

Where: \( \lambda_1, \lambda_2, \lambda_3 \) are the weight coefficients of each sub objective function.

1.2.2. Constraint equation

1) Constraint condition of tidal current equation

\[
\begin{align*}
\Delta P_j &= \sum_{k=1}^{m} P_j - U_j \sum_{k=1}^{m} U_k (G_{jk} \cos \theta_{jk} + B_{jk} \sin \theta_{jk}) = 0 \\
\Delta Q_j &= \sum_{k=1}^{n} Q_j - U_j \sum_{k=1}^{n} U_k (G_{jk} \sin \theta_{jk} - B_{jk} \cos \theta_{jk}) = 0
\end{align*}
\]  

(6)

Where: \( P_j, Q_j \) are active and reactive power injected by wind turbines. \( U_k, U_j \) are voltage amplitudes of each node. \( G_{jk}, B_{jk} \) are mutual admittances of node J and node K. \( G_{kk}, B_{kk} \) are self admittances of node K. \( \theta_{jk} \) is the voltage phase angle difference between node J and node K.

2) Constraint condition of control variable

The reactive power regulation range of wind turbine, the reactive power regulation range of SVC, and the voltage safety margin of connection point are required as control variable constraint.

\[ Q_{j_{\text{min}}} \leq Q_{j} \leq Q_{j_{\text{max}}} \]  

(7)

\[ Q_{b_{\text{min}}} \leq Q_{b} \leq Q_{b_{\text{max}}} \]  

(8)

\[ U_{l_{\text{min}}} \leq U_l \leq U_{l_{\text{max}}} \]  

(9)

Where: \( Q_{j_{\text{min}}} \), \( Q_{j_{\text{max}}} \) are the minimum and maximum value of current adjustable reactive power of compensation equipment. \( Q_{b_{\text{min}}} \), \( Q_{b_{\text{max}}} \) are the minimum and maximum value of current adjustable reactive power of wind turbine. They will fluctuate with the active power and voltage of the wind turbine. In this paper, taking the prediction method that reactive power hierarchical coordination control strategy of doubly-fed wind farm cluster in order to determine the reactive power regulation range of each wind turbine. \( U_{l_{\text{min}}} \), \( U_{l_{\text{max}}} \) are the minimum and maximum voltage of single wind farm connection point. The maximum current adjustable reactive power of wind turbine is the value after considering reactive power margin.

2. Simplified adaptive artificial fish swam algorithm

Artificial Fish Swam Algorithm (AFSA) is a new bionics optimization algorithm. This algorithm has little requirement for initial value and parameter setting. It has a strong ability to jump out of local optimum. What is more, it has strong robustness, it is simple and easy to be realized. In recent years, this algorithm has been applied in combinatorial optimization, shortest path solution, distribution network optimization and speed identifier. However, due to the evaluation of each individual in each iteration and multiple search in foraging, the algorithm still has the disadvantages of low efficiency,
long calculation time and slow convergence speed [6]. To solve the above problems, the Simplified Adaptive Artificial Fish Swarm Algorithm (SAAFSA) is proposed.

2.1. Initialization of SAAFSA
In SAAFSA, in order to increase the diversity of the initial population and avoid the problem that the random initial artificial fish swarm causes the algorithm to fall into local optimum at the initial stage, the position of artificial fish is evenly distributed in the range of control variables. The control variable interval is evenly divided into N intervals, where N is the number of artificial fish population, and a random initial artificial fish is generated in each interval.

2.2. Simplify optimization behavior of SAAFSA
Considering the simplicity and practicability of the optimization algorithm, in order to find the optimal value quickly, the center position of artificial fish swarm behavior is added to the tailing behavior formula. The improved tailing behavior formula is as follows

\[ X_{i+1} = X_i + \text{Rand}(\cdot) \cdot \text{Step} \cdot \frac{X_{\text{max}} - X_i}{X_{\text{max}} - X_i} + \text{Rand}(\cdot) \cdot \text{Step} \cdot \frac{X_c - X_i}{X_c - X_i} \]  

In the iterative process of SAAFSA, the artificial fish only do foraging behavior in the early stage of iteration. When the individual artificial fish swarm together to form a certain scale or the optimization algorithm is in the middle and late stage of iteration, the artificial fish will choose the following behavior first.

2.3. Adaptive parameters of SAAFSA
In AFSA, both the perceptual distance and the moving step size are fixed values. Larger perceptual distance and moving step size represent stronger global search ability, while smaller perceptual distance and moving step size represent stronger local search ability. If the perceptual distance and moving step size show a decreasing trend in the iterative calculation, it can make the AFSA have strong global search ability in the initial stage of algorithm optimization, and can quickly gather around the optimal value. With the deepening of optimization, the perceptual distance and moving step size gradually decrease, which can make it have strong local search ability and can accurately search the optimal value. Therefore, the ability to coordinate global search and local search by adaptively changing perceptual distance and moving step size is positive to AFSA. The perceptual distance and moving step size of SAAFSA are adjusted as follows

\[
\begin{align*}
\alpha &= \exp(-30 \cdot (m / M_{\text{max}}))^3 \\
\text{visual} &= \text{visual} \cdot \alpha + \text{visual}_{\text{min}} \\
\text{step} &= \text{step} \cdot \alpha + \text{step}_{\text{min}}
\end{align*}
\]  

Where: \( \text{visual}_{\text{min}} \) is the minimum perceptual distance are, \( \text{step}_{\text{min}} \) is the minimum moving step, \( m \) is current iterations, \( M_{\text{max}} \) the maximum number of iterations.

3. Simulation analysis
This section takes a wind farm cluster in a certain area as an example to verify the feasibility of the control strategy through simulation analysis. There are three single farms in the wind farm cluster. The statistical information of the installed capacity and the number of wind turbines in each farm is shown in table 1.
Table 1. Statistical information table of installed capacity of each wind farm.

| Wind Farm   | Installed Capacity | Number of Wind Turbine |
|-------------|--------------------|------------------------|
| #1 wind farm | 198MW              | 132                    |
| #2 wind farm | 102MW              | 68                     |
| #3 wind farm | 99MW               | 50                     |

The total installed capacity of the wind farm cluster units is 399MW. The wind turbines are 1.5MW DFIG and 2.0MW DFIG. The wind turbine is connected to the box transformer through cable lines to form a unit connection, and the box transformer increases the wind turbine voltage from 0.69kV to 35kV. In the simulation example system of this chapter, the reference capacity is 100MVA, and the reference voltage of wind farm cluster connection point is 1.0p.u.. Taking #2 wind farm as an example, the optimization effect of wind farm and reactive power of wind turbine are illustrated.

In order to compare the effects of different control strategies and optimization algorithms on the voltage regulation effect of grid connection point and optimization effect of farm cluster, the following two control methods are used for comparison.

In mode 1, the minimum voltage deviation at the grid connection point of the wind farm cluster is taken as the control objective. After the reactive power task of the wind farm cluster is obtained, the reactive power is allocated according to the reactive power output capacity of the wind turbine. That is, the stronger the reactive power of the wind turbine is, the more reactive power is generated, and the control cycle is 10 minutes. If the total reactive power of wind turbine exceeds the limit, the compensation device will bear the lack of reactive power.

In mode 2, the reactive power of each wind turbine and reactive power compensation equipment is solved by using the reactive power and voltage control strategy, mathematical model and optimization algorithm proposed in the previous section. In order to simplify the calculation, the branches in each single field are considered to meet the adjacent conditions, and the control period is 10 minutes.

Figure 2 shows the actual active power curve of the wind farm cluster. The voltage at the grid connected point of wind farm cluster will change with the change of active power.

![Active power curve of wind farm cluster](image)

It can be seen from Fig. 3 that both mode 1 and mode 2 can optimize the voltage at the grid connection point of wind farm cluster to a certain extent. In mode 1, reactive power is roughly distributed according to the reactive power output capacity of wind turbine. After optimization, there is still a certain deviation between the optimized grid point voltage and the reference voltage. The maximum voltage deviation can reach 3.092kV, and the voltage fluctuation of the grid point is large within 24 hours. It is explained that mode 1 only increases the voltage at the grid connection point and cannot stabilize the voltage near the reference voltage. In mode 2, the hierarchical control strategy is used to track the change of voltage of the grid connection point for reactive power distribution. The
calculated reactive power is more accurate and the control effect is better. The voltage deviation of grid connection point of wind farm cluster is smaller, the maximum voltage deviation is 0.902kV, and the voltage fluctuation is also small within 24 hours.

![Figure 3](image.png)

**Figure 3.** The control effect of voltage at the grid connection point under different control modes

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**References**

[1] Yang J, Jin X, Wu X, et al. An Improved Current Load Distribution Control Strategy for DC Microgrid [J]. Proceedings of the CSEE, 2016, 36 (1): 59-67.

[2] Lin P, Wang P, Xiao J, et al. An Integral Droop for Transient Power Allocation and Output Impedance Shaping of Hybrid Energy Storage System in DC Microgrid [J]. IEEE Transactions on Power Electronics, 2017: 1-1.

[3] Yang J, Jin X, Wu X, et al. Non-interconnection communication network power allocation strategy of hybrid energy storage system in DC microgrid [J]. Journal of China Electrotechnical Society, 2017, 32 (10): 135-144.

[4] Oliveira T R, Donoso-Garcia P F. Distributed Secondary Level Control for Energy Storage Management in DC Microgrids [J]. IEEE Transactions on Smart Grid, 2016, PP (99): 1-11.

[5] Mi Y, Wu Y, Zhu Y, et al. Coordinated control of independent DC microgrids with automatic distribution of load power [J]. Power System Technology, 2017, 41 (2): 440-447.

[6] Abeyasekera, T., Johnson, C. M., Atkinson, D. J., & Armstrong, M. (2005). Suppression of line voltage related distortion in current controlled grid connected inverters. IEEE Transactions on Power Electronics, 20 (6), 1393-1401.