Intelligent Optimization Design of Reactive Voltage Sensitivity Parameters for Large-Scale Distributed Wind Farms

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Abstract. Aiming at the problem that the reactive voltage sensitivity parameter of large-scale distributed wind farm is low overall, the parameter intelligent optimization design of the reactive voltage sensitivity of large-scale distributed wind farm is carried out. Firstly, design a wind farm equivalent circuit and optimize the parameters of the traditional reactive voltage sensitivity optimization model, and set the objective function to adjust the model weight coefficient. Then the bat algorithm is improved according to the parameter intelligent optimization model, and the reactive volt sensitivity parameter of the scaled distributed wind farm is intelligently optimized according to the improved bat algorithm. Finally, a simulation experiment is carried out to test the performance of intelligent optimization of reactive voltage sensitivity parameters of large-scale distributed wind farms. It is concluded that the reactive power sensitivity parameter of the large-scale distributed wind farm reactive voltage sensitivity parameter optimization is significantly higher than that of the reactive voltage sensitivity parameter optimized by the traditional reactive voltage sensitivity parameter optimization method.

Keywords: Scale · Decentralized · Wind farm · Reactive voltage · Sensitivity · Parameters · Intelligent optimization

1 Introduction

Reactive voltage sensitivity is no stranger to large-scale distributed wind farm electric power workers. With the increase of voltage level of transmission system, the problem of reactive voltage sensitivity has been paid more and more attention [1]. However, there is no unified conclusion on the concept of reactive voltage sensitivity [2]. In the relevant report, the IEEE believes that if the large-scale distributed wind farm power system can maintain the voltage, so that when the load increases, the power consumed by it will also increase. At this time, the wind farm power system is in a state where the reactive voltage sensitivity is high. On the contrary, the wind farm power system is in a

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state where the reactive voltage sensitivity is low [3]. In general, high reactive voltage sensitivity means that when the wind farm power system is operating under given initial conditions, the sudden increase in load or the change in system structure still has the ability to maintain all nodes operating sensitively. The essence is that the system has sufficient safety margin when facing these emergencies [4]. The reactive voltage sensitivity reduction refers to the process in which the reactive voltage sensitivity value is lower than the specified range when the wind farm power system is operating, and the reactive voltage sensitivity value is gradually attenuated [5]. Most of the performance of the reactive voltage sensitivity reduction phenomenon is the continuous decline of the reactive voltage sensitivity, but the instability of the reactive voltage sensitivity rise also exists and occurs [6]. The collapse of reactive voltage sensitivity means that when the wind farm power system is in a state of large voltage instability, the load continues to try to increase the current to obtain more power. This reduces the reactive voltage sensitivity to an unacceptable range [7]. Intelligent optimization design of reactive voltage sensitivity parameters can effectively improve the reactive voltage sensitivity of large-scale distributed wind farms [8].

2 Intelligent Optimization Model Design of Reactive Voltage Sensitivity Parameter

2.1 Wind Farm Equivalent Circuit Design

Because of the randomness and uncontrollability of wind speed and the difference of wind speed in the wind farm, the wind turbine group division is different from the traditional synchronous generator group. Wind farms are generally built in remote areas, and the environmental conditions are relatively poor. Wind turbines run in dynamic environment with changing wind speed and wind direction. The traditional methods of calculating the output power of wind farms depend on the standard power characteristic curve of wind turbines provided by the manufacturers. There may be differences between the actual operation conditions and the design conditions of the wind turbine; in addition, the factors that change the structural parameters or operation mode of the wind turbine in the long-term operation process will also have an impact on the performance of the wind turbine, resulting in the difference between the actual operation characteristics and the design of the wind turbine. The actual operation of the wind turbine does not necessarily follow the static wind speed power characteristic curve given in the technical manual under the specific operation environment.

For large wind farms with complex terrain and irregular layout, the principle of grouping wind turbines with the same or similar operating points is adopted, and the equivalent wind farm of multi typhoon generator model is used. Considering the active and reactive power output and voltage of each wind turbine, these important output characteristics integrate the operation information of wind turbine, such as the operation environment, the fluctuation of wind speed, speed and parameters of wind turbine, including the dynamic information of wind turbine when the wind speed fluctuates, and can also directly and accurately reflect the operation point of wind turbine. The wind speed of wind turbines in different locations may be close to or greatly different, and even the wind speed measured by two wind turbines with similar geographical locations may be quite different. It can be concluded that the wind speed can not only reflect the size of the wind force acting on the blades of the wind turbine, but also reflect the topography of the installation location of each wind turbine unit and the mutual influence of adjacent wind turbines in the wind speed. Therefore, the actual measured wind speed data can be used for cluster division. The measured active power of each wind turbine unit is the final result of the physical process that its wind speed is transformed into electric energy through complex wind energy. It is the final comprehensive feedback of the wind speed, geographical location, terrain and actual operation performance of each wind turbine unit to the grid,

Grid connected operation of wind power generation is an effective way to realize large-scale wind energy development and utilization. However, unlike conventional energy, wind energy is a kind of random energy with small energy density, which has the characteristics of "intermittence" and "randomness", which leads to the output power of wind farms fluctuating with the change of wind speed being uncontrollable and unpredictable. When the wind speed is large, the power generation of the wind farm is large; when there is no wind or the wind speed is very small, the power generation of the wind farm is zero. However, the wind speed depends on the natural conditions, which will change every moment. In recent years, with the increasing number of wind farms and the increasing scale of wind farm construction, wind farms have become an important part of power grid. The fluctuation of wind farm output power will bring many adverse effects on the safety, stability and economic operation of the power system. Reactive power reflects the reactive power compensation of the wind farm; electricity and current reflect the operation of each connecting line of the wind farm; various temperatures of the wind turbine reflect the operation of the wind turbine itself. But compared with these data, wind speed and active power are more closely related to the fluctuation of wind farm output power, which can more reflect the actual fluctuation of wind farm output power. Therefore, the wind speed measurement data or active power measurement is selected as the basis for cluster classification. If the wind farm is composed of several different types of wind turbines, first of all, it is necessary to divide the wind turbines according to the type and capacity of the wind turbines, and then take the actual wind speed or active power in a certain period of time as the input of the data sample based on the spectral clustering algorithm to obtain Wind turbine group division results.

The wind farm equivalent circuit used in the wind farm electric field sensitivity parameter intelligent optimization model is shown in Fig. 1.

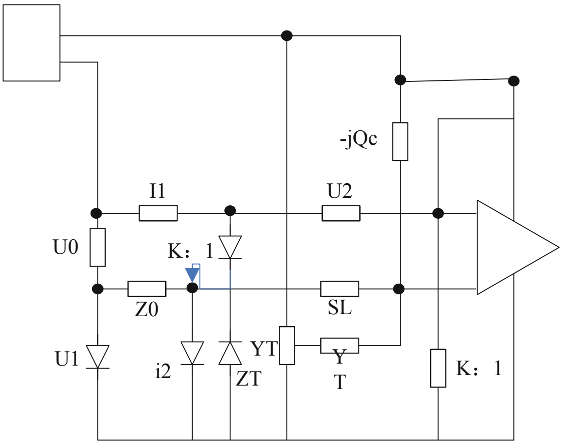

Fig. 1. Wind farm equivalent circuit

U1 and U2 are the high and low voltage side voltages of the substation, ZT and YT are the transformer impedance and the excitation admittance, k is the transformer ratio, and SL is the total load on the low voltage side of the transformer. QC is the reactive power compensation capacity of the low-voltage side of the transformer, Z0 is the equivalent impedance of the upper system of the substation, and U0 is the equivalent voltage of the upper system. It is calculated by the measured high-voltage side voltage U1 of the wind farm and the voltage loss of the upper system line. Regardless of the voltage characteristics of the load, when the capacitor bank is switched or the main transformer tap position is adjusted, it is considered that the upper system equivalent voltage U0 and the load power SL remain unchanged [9].

2.2 Parameter Optimization

In the optimization of reactive voltage sensitivity parameters of large-scale distributed wind farms, the primary criterion to be met is the voltage pass rate [10]. Then, each time the transformer tap and the capacitor are operated, it takes cost and time, and the cost of the tapping operation is high. The number of times of tapping and capacitor operation is minimized under the condition of ensuring the voltage qualification rate. Then, the power supply bureau also has operational requirements for the high-voltage side power factor of the large-scale distributed wind farm, but it is not a strict assessment index. For a 110 kV large-scale distributed wind farm, its power factor is required to meet the operational requirements as much as possible, and too much reactive power cannot be reversed to the higher-level system. Finally, the low-voltage side voltage of the large-scale distributed wind farm must meet the reverse voltage control requirements as much as possible to ensure that the high-voltage side power factor can be adapted to the reactive power requirements of the superior system.

2.3 Objective Function Setting

Under the condition that the number of times of control equipment is not given, the objective function of the intelligent optimization model of reactive voltage sensitivity parameter of large-scale distributed wind farm is set as follows:

$$\begin{aligned} \min J_1 = & \alpha_1\left(1-\frac{N_{Uqua}}{N}\right)+\alpha_2\frac{K_{Tap}}{K_{T\max}}+\alpha_3\frac{K_C}{K_{C\max}}+\alpha_4\left(1-\frac{N_{\cos\varphi qua}}{N}\right) \\ & +\alpha_5\sum\nolimits_{t-1}^{N}\left|U_{2t}-U_{2t,aim}\right|+\alpha_6\sum\nolimits_{t-1}^{N}\left|COS\varphi_{1t}-COS\varphi_{1t,aim}\right| \end{aligned} \quad (1)$$

(1) Where, J1 is the objective function, the optimization target is the minimum value of J1, N is the number of time periods of the day, N_{Uqua} is the number of qualified periods of the low-voltage side of the day, and K_{Tap} is the number of times of the transformer tapping day. K_{Tmax} is the maximum number of movements allowed by the transformer tap, K_C is the number of movements of the capacitor group in one day, K_{Cmax} is the maximum number of movements allowed by the capacitor, and $N_{cos\varphi qua}$ is the number of qualified periods of the high-voltage side of the day. U_{2t} is the low-voltage side voltage of the t-th period, $U_{2t,\ aim}$ is the low-voltage side voltage control target of the t-th period, and cosφ1t is the high-voltage side power factor of the t-th period. cosφ1t, aim is the high-voltage side power factor control target for the t-th period, and α1 ~ α6 are the weight coefficients.

The first term of the above objective function J1 represents the voltage failure rate, and the calculation formula of the voltage yield is the sum of the time of the monitoring point voltage within the acceptable range and the percentage of the total time N of the voltage monitoring [11, 12]. Similarly, the fourth term of the objective function represents the high-voltage side power factor failure rate of a large-scale distributed wind farm for one day. The fifth term of the objective function indicates the degree of deviation of the low-voltage side voltage from the voltage control target, and the voltage control target is set according to the inverse voltage regulation principle.

The sixth term of the objective function indicates the degree of deviation of the high-voltage side power factor from the power factor control target, and the power factor control target is matched with the reactive demand of the superior system. According to the importance of the power system to each index, the corresponding weight coefficient is selected. In this model, α1 = 105, α2 = 104, α3 = 103, α4 = 102, α5 = 10, and α6 = 1 are set. The intelligent optimization model of reactive voltage sensitivity parameter does not treat voltage amplitude safety and power factor safety as hard constraints, but modifies it to voltage yield rate and power factor yield as indicators in the objective function. The reason is that due to the limitation of the number of times of control equipment operation and the fluctuation of the scaled distributed wind farm load and voltage [13, 14]. If the optimal operation of the control equipment cannot meet the requirements of the voltage-reliable all-day qualification of the large-scale distributed wind farm, it is necessary to ensure the highest pass rate and power factor pass rate of the large-scale distributed wind farm throughout the day. Therefore, the voltage pass rate and the power factor pass rate index are added to the objective function.

2.4 Adjustment Weight Coefficient

Through the solution of the model, the optimality of the objective function corresponding to different weight coefficients is found under the constraint condition. The change of the number of times of control equipment has a certain influence on the control effect of reactive voltage sensitivity. According to the objective function, the comprehensive optimal result of each index can be obtained theoretically [15–17]. However, due to the influence of the algorithm or the number of iterations, not every calculation can obtain the global optimal solution. At the same time, in order to explore the influence of the change of the number of times of control equipment on the control effect of the reactive voltage sensitivity of the scaled distributed wind farm, if the decrease in the number of times the control device is operated has little effect on the control effect, the number of actions can be continuously reduced until the important indicator fails. The grid dispatcher of large-scale distributed wind farms is provided with various control effects optimization schemes, and the dispatcher can select the next-day optimization scheme according to the operation experience [18, 19]. The objective function of the intelligent optimization model of reactive voltage sensitivity parameter is affected by the change of the number of actions of the control device:

$$\begin{aligned} \min J_2 = \alpha_1\left(1-\frac{N_{Uqua}}{N}\right)+\alpha_2\left(1-\frac{N_{\cos\varphi qua}}{N}\right)+\alpha_3 \\ \sum\nolimits_{t-1}^{N}\left|U_{2t}-U_{2t,aim}\right|+\alpha_4\sum\nolimits_{t-1}^{N}\left|COS\varphi_{1t}-COS\varphi_{1t,aim}\right| \end{aligned} \tag{2}$$

(2) In the formula, J_2 is the objective function, the optimization target is the minimum value of J_2, the meanings of other variables are the same as the first formula, and $\alpha1 \sim \alpha4$ are the weight coefficients, taking $\alpha1 = 105$, $\alpha2 = 102$, $\alpha3 = 10$, $\alpha4 = 1$. In addition, it is necessary to improve the constraint of the maximum number of action times of the transformer daily maximum number of times of the capacitor, and the specific limit values of the number of times of operation of the control device are as follows:

$$\begin{aligned} \sum\nolimits_{t-1}^{N} C(t-1)+C(t) = n_{Qg}\left(n_{Qg}\le n_Q\right) \\ \sum\nolimits_{t-1}^{N} Tap(t-1)+Tap(t) = n_{Tg}\left(n_{Tg}\le T\right) \end{aligned} \tag{3}$$

(3) Where N is the total number of time periods in a day, $C(t-1) + C(t)$ represents the number of change groups of the capacitor bank from the t-1 period to the t period, and n_{Qg} is the number of times the capacitor bank is given. n_Q is the maximum number of operations allowed for the capacitor bank. $Tap(t-1) + Tap(t)$ indicates the value of the change of the tap from the $t-1$ period to the t period, and n_{Tg} is the number of times the tap is given, n_T is the maximum number of actions allowed by the tap [20].

The above objective function J2 reduces the index of the number of times of tap and capacitor group daily action with respect to J1, and gives a specific limit value of the number of times of operation of the control device in the constraint condition. The purpose of J2 is to obtain a variety of optimization schemes by continuously reducing the number of times of tapping and capacitor operation, and to explore the influence degree of the change of the number of times of control equipment on the reactive voltage sensitivity control effect of large-scale distributed wind farms. The grid dispatcher of large-scale distributed wind farms is provided with various control effects optimization schemes, and the dispatcher can select the next-day optimization scheme according to the operation experience. After the design of the intelligent optimization model of reactive voltage and sensitivity parameters of large-scale distributed wind farms is completed, the optimization parameters of reactive voltage sensitivity need to be calculated to complete the intelligent optimization design of reactive voltage sensitivity parameters of large-scale distributed wind farms.

3 Improved Bat Algorithm Based on Parameter Intelligent Optimization Model

1) Initialization. Set large-scale distributed wind farm parameters and algorithm parameters, including population size popsize, maximum iteration number K_{max}, inertia factor ω, maximum speed limit V_{max} and other parameters.
2) The initial population is produced. Under the condition that the variation range of the control variable is satisfied, the initial position X_i and the initial velocity V_i of each bat in the population are randomly assigned.
3) Position correction. For a bat that does not satisfy the constraint of the minimum time interval between two adjacent actions of the control device, the bat is improved according to the "position correction strategy that considers the minimum time interval of the two adjacent actions of the control device". The bat that does not satisfy the constraint condition of the maximum number of movements of the control device is improved according to the "position correction strategy that takes into account the maximum number of movements of the control device."
4) Power flow calculation, fitness evaluation. The Newton-Raphson iterative method is used to calculate the power flow. The fitness value f(Xi) of each bat is evaluated according to the power flow calculation results, and the optimal solution of each bat and the optimal solution of the population are found and stored. The formula for calculating the fitness value is:

$$f(X_i) = 1/J_i \tag{4}$$

Where J_i is the objective function of the i-th bat.

5) The bat algorithm starts iterating, updating the iteration number k and the inertia factor ω.
6) Global search. According to the frequency of each bat updated F_i and speed V_i.
7) Guided by a feasible direction. First, the bats with unqualified power factor are improved according to the "speed correction strategy considering power factor

safety". Then, the bat with unqualified reactive voltage sensitivity parameters is improved according to the "speed correction strategy considering the safety of the reactive voltage sensitivity parameter". If the speed exceeds the maximum speed limit V_{max}, it is limited to V_{max}.

8) Location update. Update the position Xi of the bat, if the position exceeds the defined range of the control variable, it is limited to the boundary of the defined range. And follow step 3 to re-position the position.
9) Neighborhood search. When a random number is greater than the pulse emissivity r_i, a random walk is performed; if a random number is not greater than the pulse emissivity r_i, no random walk is performed.
10) Fitness evaluation and convergence judgment. The Newton-Raphson iteration method is used to calculate the power flow, and the fitness value $f(X_i)$ of each bat is re-evaluated, and the individual optimal solution and the optimal population solution are updated and stored. Then it is judged whether the number of iterations k reaches the maximum number of iterations K_{max}, or the optimal solution of the population remains unchanged for 10 consecutive generations. If so, the program ends and the optimal individual is output; otherwise, the process proceeds to step 5 to continue the iteration.

The bat algorithm is improved by the intelligent optimization model of reactive voltage sensitivity parameter, the optimization parameters of reactive voltage sensitivity are calculated, and the sensitivity parameters of reactive voltage of large-scale distributed wind farm are intelligently optimized.

4 Intelligent Optimization Based on Improved Bat Algorithm

The bat algorithm is a new type of heuristic intelligent algorithm. Compared with traditional intelligent algorithms such as genetic algorithm and particle swarm algorithm, it has more advantages in global search ability and calculation speed. Of course, similar to the traditional intelligent algorithm, there are also a large number of invalid searches in the random search process of the bat algorithm. The expert experience of guiding the feasible direction in the dynamic reactive power optimization calculation also plays an important role in improving the random search efficiency of the bat algorithm. Therefore, a feasible direction guiding strategy for dealing with the adaptive optimization model of reactive voltage and sensitivity parameters of large-scale distributed wind farms is proposed to improve the random search efficiency of the bat algorithm. The improvement strategy of the bat algorithm mainly has the following four points: a speed correction strategy considering the safety of the reactive voltage sensitivity parameter. When the reactive voltage sensitivity parameter is unqualified, the feasible direction guiding strategy is used to correct the speed direction and step size of the algorithm; considering the power factor safety speed correction strategy. When the power factor is unqualified, the feasible direction guiding strategy is used to correct the speed direction and step size of the algorithm; considering the position correction strategy of controlling the minimum time interval constraint of the adjacent two actions of the device. When the minimum time interval constraint condition of the adjacent two actions is not satisfied, the position correction strategy is used to correct the position of the algorithm; and the position correction strategy of controlling the maximum action number of the device is considered. When the maximum action number constraint condition is not satisfied on the day, the "peak clipping and valley filling" strategy is adopted to ensure that the equipment daily allowable action number constraint is satisfied.

5 Simulation Experiments

In order to ensure the effectiveness of the experiment, the traditional reactive voltage sensitivity parameter optimization method is compared with the intelligent optimization method of the reactive voltage sensitivity parameter of the scaled distributed wind farm, and the test results are observed. The bat algorithm parameters are set to: population size popsize = 20, maximum iteration number $K_{max} = 100$, maximum limit speed of taps and capacitors $V_{i,max} = 1$, the constant $\alpha = 0.9$, the constant $\gamma = 2$, the pulse emissivity $ri^0 = 0.6$, the minimum frequency $F_{min} = 0$, and the maximum frequency $F_{max} = 2$. The simulation conditions are: hardware platform: desktop computer, processor Intel(R) Core(TM)2 Duo CPU E7200 @2.53 GHz, memory 1.99 GB, hard disk 120 GB, Windows XP 32-bit operating system. Software platform: Matlab 7.10.0 (R2010a). The experimental results are shown in Fig. 2.

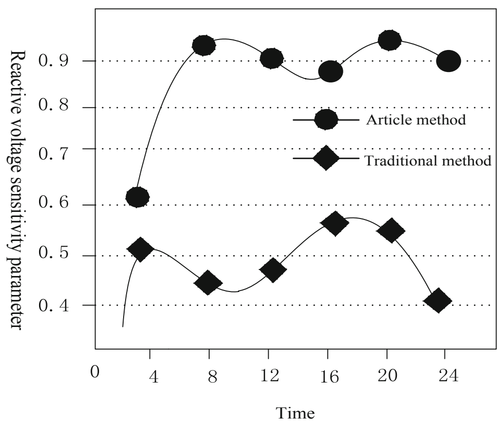

Fig. 2. Reactive voltage sensitivity parameters under intelligent optimization method

By comparing the reactive power and voltage sensitivity parameters of large-scale distributed wind farms after the intelligent optimization method, the traditional reactive power and voltage sensitivity parameter optimization method is adopted, and it can be found that after the intelligent optimization model is established, the reactive power and voltage sensitivity parameters of the whole day can be obtained The parameters of reactive power and voltage sensitivity are studied, and the intelligent optimization method of reactive power and voltage sensitivity parameters based on bat algorithm is improved. Most of them are kept above 0.9, which shows that it improves the sensitivity of reactive power and voltage sensitivity. The parameters of large-scale distributed wind farms are obviously higher than the traditional optimization methods of reactive power and voltage sensitivity parameters

6 Conclusion

Most of the wind power bases are located in remote areas of the land or at sea, especially large-scale distributed wind farms. Because the wind farms are far away from the load center, their long-distance transmission power has fluctuations. Therefore, the reactive voltage sensitivity parameter is not stable enough. The intelligent optimization method for reactive voltage sensitivity parameters of large scale distributed wind farm combining the intelligent optimization model of reactive voltage sensitivity parameter and the bat algorithm based on the intelligent parameter optimization and optimization of the sensitivity parameter can intelligently optimize the reactive voltage sensitivity parameter of the scaled distributed wind farm to significantly improve the sensitivity of reactive voltage sensitivity parameters of large scale distributed wind farms.

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