Analysis of distributed power sources impact on distribution network voltage and reactive power optimization

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Abstract. The grid connection of distributed power sources will greatly change the initial electrical state of the system. Therefore, it is necessary to do scientific research on the impact of grid connection of distributed power sources and take appropriate measures to improve system stability. Two evaluation indexes of average voltage change rate and average voltage fluctuation rate are established to describe the impact of different distributed power grids on voltage. The IEEE 33-node power distribution network is used as a model. The distributed power source is connected to the power distribution network with different capacities and different locations. Based on the calculation results of the power flow, the voltage distribution diagrams of the system under different states are drawn, and a comprehensive analysis is performed according to the formulated quantitative indicators. A genetic algorithm was used to search for the optimal reactive power output of a single power supply connected to the grid.

1. Introduction
Today's world economy is developing rapidly. At the same time, it brings huge energy consumption and severe environmental pollution[1-3]. To achieve the strategic goals of sustainable development, sustainable energy supply is essential. Therefore, the development and utilization of new energy and the development of smart grids have become important strategies for energy development in various countries around the world[4-5]. Because the distributed power is connected to the distribution network, the magnitude and direction of the tide will change greatly, and the voltage of the distribution network will change. Therefore, it is necessary to connect the distributed power to the grid.

Based on the previous work, this paper develops corresponding evaluation indicators to quantify the degree of influence of different distributed power grids on the system voltage. The genetic algorithm is used to search for the optimal reactive power output of a single power grid to achieve the goal of minimizing the average system voltage fluctuation.

2. Analysis of the impact of distributed power grid connection on voltage
2.1. Theoretical analysis
Preventing large voltage drops and voltage fluctuations is one of the most important issues when designing and managing distributed power grids. To briefly illustrate the impact, an ideal distribution network model is shown in Figure 1.

\[ \Delta U_i = \frac{P_{R1} + Q_{X1}}{U_N} \]  
(1)

The voltage drop across \( R_2 + jX_2 \) is:

\[ \Delta U_2 = \frac{P_{R2} + Q_{X2}}{U_N} \]  
(2)

If the distribution of active power is \( P_{G2} \) and reactive power is \( Q_{G2} \) at node 2 Power supply, the voltage of node 2 becomes:

\[ U_2 = U_0 - \Delta U_1 \cdot (P_{G2} - Q_{G2}) \cdot X_2 \frac{X_2}{U_N} \]  
(3)

According to the above formulas, when the distributed power is connected to the grid, the node voltage level of the system itself will be greatly changed. Distributed power is usually provided with reactive power compensation, so when it is connected to a node in the system, the active and reactive power flowing through the node before it are reduced, so the maximum load that the line can withstand also increases the capacity of the power grid.

2.2. Impact of grid-connected distributed power on voltage

The average voltage change rate is used for quantization to achieve a more accurate analysis of the impact mechanism. A larger value indicates a greater degree of voltage change after grid connection. The specific quantification method is to subtract the initial voltage by the node voltage according to the corresponding node number after the grid connection of the distributed power source, and then use the initial node voltage as the corresponding voltage reference to find the voltage change rate of a single node, and then accumulate and sum to obtain the overall system voltage change. Divide the voltage change rate of the whole system by the total number of system nodes to get the average voltage change rate of the system. The algorithm is shown in equation (4).

\[ C_m = \frac{1}{n} \sum_{i=1}^{n} \frac{V_i - V_{0i}}{V_{0i}} \]  
(4)

In the formula, \( C_m \) is the average voltage change rate, \( m \) is the access point number, \( i \) is the node number, \( n \) is the total number of system nodes, \( V_i \) is the current node voltage amplitude, and \( V_{0i} \) is the original node voltage amplitude.

The average voltage fluctuation rate is introduced to quantify the system voltage fluctuation in different states. The specific quantification method is to take the standard voltage of each node as the standard threshold value "1", subtract the standard voltage from the current voltage of each node in the system, and sum it up to obtain the current voltage fluctuation level of the system, and then divide by the total number of system nodes. The average voltage fluctuation rate of the system is obtained, and its calculation method is shown in equation (5).

\[ F_f = \frac{1}{n} \sum_{i=1}^{n} |V_i - 1| \]  
(5)

In the formula, \( F_f \) is the average voltage fluctuation rate, \( n \) is the number of system nodes, \( i \) is the node number, and \( V_i \) is the current node voltage amplitude.
3. Mathematical model of dynamic reactive power optimization in distribution network

Reactive power optimization of the distribution network refers to the optimization of the gear and reactive power of the on-load tap-changer transformers based on the existing network structure and reactive power compensation devices, and on the premise of the known system load.

3.1. Objective function

In order to make the system voltage reach the lowest fluctuation, the minimum average voltage fluctuation rate is selected as the objective function, namely:

$$\min F_i = \frac{1}{n} \sum_{i=1}^{n} |V_i - V_{i-1}|$$  \hspace{1cm} (6)

In the formula, $F_i$ is the average voltage fluctuation rate of the system, $n$ is the number of nodes, $i$ is the node number, and $V_i$ is the current node voltage amplitude.

Constraints for mathematical models of reactive power optimization in distribution networks include equality constraints and inequality constraints. Each period of dynamic reactive power optimization must meet the relevant constraints.

3.2. Equality constraint

The grid-connected power supply must meet the active and reactive power constraints of the system:

$$P_{DG_i} - P_{Di} = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})$$

$$Q_{DG_i} - Q_{Di} = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij})$$  \hspace{1cm} (7)

3.3. Inequality constraints

In the formula, $P_{DG_i}$ and $Q_{DG_i}$ represent the active and reactive power output of the distributed power source, $P_{Di}$ and $Q_{Di}$ represent the active load and reactive load of node $i$, and $G_{ij}$ and $B_{ij}$ represent the conductance and susceptance between nodes $i$ and $j$, respectively. The control variable constraint expression in the inequality constraint is:

$$Q_{DG_{imin}} \leq Q_{DG_i} \leq Q_{DG_{imax}}, i = 1, 2, \ldots, N_G$$

$$Q_{C_{jmin}} \leq Q_{C_{j}} \leq Q_{C_{jmax}}, j = 1, 2, \ldots, N_C$$

$$K_{TK_{imin}} \leq K_{TK_i} \leq K_{TK_{imax}}, i = 1, 2, \ldots, N_T$$  \hspace{1cm} (8)

In the formula, $Q_{DG_{imin}}$ and $Q_{DG_{imax}}$ respectively represent the minimum and maximum reactive power capacity of distributed power, $Q_{C_{jmin}}$ and $Q_{C_{jmax}}$ respectively represent the minimum and maximum reactive power capacity of reactive power compensation equipment, and $K_{TK_{imin}}$ and $K_{TK_{imax}}$ represent on-load voltage regulation Minimum and maximum transformer ratios.

4. Principle of genetic ant colony algorithm

The access of distributed power sources further aggravates the difficulty and complexity of optimization. Traditional intelligent algorithms such as genetic algorithm, particle swarm algorithm, and firefly algorithm have not achieved good optimization results. In this paper, genetic algorithm and particle swarm algorithm are combined to take advantage of the advantages and complementary advantages of the two algorithms, and overcome their defect.

Genetic algorithm is a kind of random search algorithm based on biological natural selection and genetic mechanism. The three basic operators of the algorithm are selection, crossover and mutation.

The basic idea of particle swarm algorithm is to randomly initialize a group of particles and find the optimal solution during continuous iteration. The traditional particle swarm algorithm has similar initial particles, which leads to slower convergence speed of the algorithm. In combination with relevant literature, this article uses the chaotic sequence initializes the position and velocity of the population, thereby ensuring the randomness and diversity of the initialized particle swarm. The process of particle swarm position and velocity initialization is as follows:
The position change of the particles is expressed by the following formula:

\[ v_{id}^{t+1} = wv_{id}^{t} + c_1 \text{rand}_1(p_{best \_{id}}^{t} - x_{id}^{t}) + c_2 \text{rand}_2(g_{best \_{id}}^{t} - x_{id}^{t}) \]  

(9)

The position change of the particles is expressed by the following formula:

\[ x_{id}^{t+1} = x_{id}^{t} + v_{id}^{t+1} \]  

(10)

Where \( w \) is the inertia weight factor used to adjust the optimization ability; \( t \) is the number of iterations; \( c_1 \) and \( c_2 \) are acceleration coefficients, which are always positive; \( \text{rand}_1 \) and \( \text{rand}_2 \) are random numbers uniformly distributed in the range \([0,1]\).

5. Example analysis

The IEEE 33-node system is used as a simulation model, and the quantified indicators are used to describe the degree of change in voltage before and after. The IEEE 33-node system is a radial power distribution network with a reference power of 10MVA, a voltage level of 12.66 kV, a total active load of 3715 kW, and a total reactive load of 2300 kVar. The system parameters are described in [6]. Network structure as shown in picture 2.

Nodes 3, 10, 17, 21, 24, and 30 are selected as the access points, among which node 3, node 10, and node 17 occupy the front, middle, and rear of the IEEE 33 node system trunk respectively, and nodes 21, 24, and 30 respectively occupy three branches of the IEEE 33-node system. The access capacity is 10% to 30% of the total load capacity of the IEEE 33 node system. The specific capacity is shown in Table 1.

Table 1. Distributed power access capacity with different penetration rates.

| Distributed power penetration | Input active power / kW | Input reactive power / kVar |
|-------------------------------|-------------------------|-----------------------------|
| 10%                           | 372                     | 230                         |
| 20%                           | 743                     | 460                         |
| 30%                           | 1115                    | 690                         |

5.1. Influence of grid connection of distributed power on system voltage

Select nodes 2, 9, 16 and nodes 3, 10, 17 and nodes 4, 11, 18 as three sets of access points for multiple distributed power sources, and specify the access capacity of each node in the group as the total system load 10% ~ 30%. Then the impact of multiple distributed power sources on system voltage is analyzed. The clustered histograms of the values calculated with the quantified indicators are shown in Figures 3 and 4.

Figure 3. Histogram of average voltage change rate of grid-connected distributed power.
According to the analysis of the above data and voltage distribution chart, it can be obtained that:
1) Under the premise that the access position of the distributed power source remains unchanged, as its output continues to increase, the voltage amplitude of the system continues to increase;2) Multiple distributed power sources are simultaneously access will have a greater impact on the system. When the penetration rate reaches 20%, the voltage amplitudes of many nodes will increase to more than 1; 3) When multiple distributed power sources are connected to the grid, the closer the overall access location is to the end of the line, the greater the increase in voltage.

5.2. Reactive power optimization for distributed power grid connection

It can be known from Section 5.1 that connecting distributed power at the end of the system main line increases the system voltage greatly and can obtain a lower average voltage fluctuation rate. According to the dynamic reactive power optimization model of the distribution network taking into account the access of distributed power sources established in this paper, the genetic algorithm, particle swarm algorithm, firefly algorithm, and genetic particle swarm algorithm in this paper are used to dynamically perform IEEE-33 node power distribution network instances. The solution is divided into 24 periods in total. Considering the differences between the load and the distributed power source in each period, the results after dynamic reactive power optimization are shown in Table 2.

| Evaluation item          | Before optimization | Legacy algorithm | Particle swarm algorithm | firefly algorithm | The proposed algorithm |
|--------------------------|---------------------|------------------|--------------------------|-------------------|------------------------|
| Distribution network loss| 119.90              | 95.09            | 90.13                    | 89.34             | 86.52                  |
| Consumption (kW)         | 0                   | 4.32             | 6.87                     | 6.74              | 5.88                   |

6. Conclusion

This paper studies the impact of distributed power supply on the distribution network to the voltage and its reactive power optimization. The conclusions are as follows: 1) The location and capacity of the grid connection of the distributed power are important factors that change the system voltage distribution. Through the quantified indicators, it can be clearly seen that different distributed power sources have different degrees of change in system voltage, and the degree of influence varies with the location of the access to the distribution network. 2) The effectiveness and superiority of the dynamic reactive power optimization model and genetic particle swarm fusion algorithm of the distribution network that takes into account the access of distributed power sources are well demonstrated. Based on this algorithm, optimize the power input can achieve the goal of the lowest voltage fluctuation in the system.

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