Reactive Power and Voltage Optimization Control Strategy in Active Distribution Network Based on the Determination of the Key Nodes

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Abstract. The distributed generation which is integrated in the active distribution network changes power flow, bringing new challenges to the voltage control. When voltage limit violation happens, in order to make the voltage return to normal range and improve the voltage quality, a novel voltage control strategy is proposed. Considering the voltage quality and node importance, the electrical closeness centrality and key node contribution degree are defined, and the key nodes are determined by the orders of the key node contribution degree. This paper uses the reactive power compensation devices which are installed at the key nodes coordinated with the reactive power output of the distributed generation to realize the voltage optimization control. The voltage optimization control model is established by taking the minimum power loss as an objective function. Using the particle swarm optimization algorithm solves the model. The simulation results of the improved IEEE-33 bus system verify the effectiveness of the proposed method.

1. Introduction

With the large number of the distributed generation (DG) integrated to the distribution network, the traditional distribution network is gradually changing over to the active distribution network (ADN). The uncertainty of the DG may lead to over voltage or under voltage, increasing the volatility of the voltage. Thus, it is necessary to take measures to regulate the voltage and improve the voltage quality. Although the access of distributed generators brings a challenge to the voltage control, it is also a new means of voltage regulation. The authors in [1] propose a method to solve the problems of the voltage rise by means of the local reactive power control. Reference [2] utilizes the improved simulated annealing algorithm to solve the voltage optimization problems in the distributed networks with DG. Some literatures select the compensation node by using some indexes to narrow the search space. In [3], authors choose the compensation nodes based on the sensitivity analysis. Reference [4] proposes the concept of the reactive power margins, and the authors use it to determine the nodes where reactive power compensators are installed.

Reactive power compensation equipments are installed at many nodes. When the voltage is outside the range allowed, it is not necessary to regulate all the equipments. This paper proposes a novel way to realize the reactive power and voltage optimization control through determining the key nodes. When voltage limit violation happens, we can realize the voltage control just by regulating the reactive power compensation devices which are installed at the key nodes. This article is structured as follows:
the theories of the determination of the key nodes are described in Section Two. Section Three establishes the reactive power and voltage optimization control model. Section Four introduces the procedure of the proposed way with the particle swarm optimization algorithm (PSO). Section Five deals with a case study and the conclusions are discussed in Section Six.

2. Determination of the key nodes

2.1. Voltage quality contribution index

After adjusting reactive power compensators which was installed at a node, the voltage amplitude of each node in system will change. We use \( \Delta U_j \) to represent the effect on voltage of each node through the adjustment. It is defined as:

\[
\Delta U_j = \frac{U_{j,b} - U_{j,a}}{U_{j,b}} \times 100\%
\]

(1)

Where \( U_{j,b} \) is the voltage at node \( j \) before adjusting the reactive power compensators at node \( i \); \( U_{j,a} \) is the voltage at node \( j \) after adjusting the reactive power compensators at node \( i \).

The greater the value of \( \Delta U_j \) is, the voltage at the node \( j \) is closer to the rated voltage, and the improvement of the voltage quality is more obvious. In this paper, we called it voltage quality contribution index, which is regarded as an index to determine the key nodes.

2.2. Electrical closeness centrality

Since the power network can be abstracted as points and lines, the evaluation index for the importance of the nodes in the complex network theory is introduced. The importance of the nodes can be measured by centrality. This kind of index considers that the position of the nodes will affect the stability of the whole network. So far, there are many methods to evaluate the importance of each node, such as degree, betweenness, and closeness centrality. In this paper, the closeness centrality is used to measure the importance of nodes.

Closeness centrality [5] is used to measure the ability of a node which exerts influence on other nodes over the network. The greater the value is, the more important the nodes are in the network.

The closeness centrality only reflects the simple connection and interaction between nodes, and just describes the importance of each node in the power network to a certain extent. In order to reflect the electrical connection between nodes truly, we consider that the physical characteristic of the electrical network and the value of the branch impedance is used as the weight of the edge to evaluate the electrical distance between nodes. The concept of electrical closeness centrality is proposed to describe the importance of the node in power networks, and it is regarded as another index to determine the key nodes. Electrical closeness centrality of the node \( i \) is defined as:

\[
C_e(i) = \frac{N - 1}{\sum_{j=1}^{N} Z_{ij}}
\]

(2)

Where \( Z_{ij} \) represents the shortest electrical distance from node \( i \) to node \( j \); \( N \) represents the number of nodes in a network.

This index reflects whether a node is in the key position of the network from the point of view of electrical science. The greater the value of the \( C_e \) of a node is, the closer the electrical connection between the node and the other nodes are, and the voltage limit violation of the node is easier to cause the instability of the whole network.

2.3. Key node contribution degree
Taking into account the above mentioned two indexes, the key node contribution degree is defined. The different dimensional and dimensional units of these two indexes will affect the results of the data analysis. For eliminating the influence of the dimension between indexes, \( \Delta U_i \) and \( C_{(i)} \) is normalized by the following expression:

\[
y_i = \frac{x_i}{\sum x_i}
\]

(3)

Where \( x_i \), \( y_i \) are respectively the variable before and after the normalization; \( n \) is the number of the variable.

Then we can get \( \Delta U^{(i)} \) and \( C^{(i)} \), and the key node contribution degree \( K \) is defined as:

\[
K(i) = \sum_{i=1}^{n} \Delta U^{(i)} \times C^{(i)}
\]

(4)

We determine the key nodes by the order of key node contribution degree of the nodes where reactive power compensation devices are installed.

3. The model of the reactive power and voltage optimization control

Though the distributed generation connected to the voltage can make the voltage rise, it has the ability to control the reactive power and voltage. We consider the coordination of distributed generation and reactive power compensators which are shunt capacitor groups in this paper. Taking the minimum power loss as the objective function, the reactive power and voltage control optimization model is established.

3.1. Objective function

\[
\min F(x) = \min \sum_{i=1}^{N_l} \frac{P_i^2 + Q_i^2}{V_i^2} - R_i
\]

(5)

Where \( N_l \) is the number of branch; \( R_i \) is the resistance of branch; \( P_i \), \( Q_i \) are the active power and reactive power of the branch \( l \), respectively; \( V_i \) is the voltage at node \( i \).

A penalty function is used to keep the voltage within the range allowed, and we get an extended objective function as follows:

\[
\min F(x) = \min \left( \sum_{i=1}^{N_l} \frac{P_i^2 + Q_i^2}{V_i^2} - R_i + \lambda \sum_{i=1}^{N_l} \left( \frac{\Delta V_i}{V_{\text{max}} - V_{\text{min}}} \right)^2 \right)
\]

(6)

\[
\Delta V_i = \begin{cases} V_i - V_{\text{max}} & V_i > V_{\text{max}} \\ 0 & V_{\text{min}} \leq V_i \leq V_{\text{max}} \\ V_{\text{min}} - V_i & V_i < V_{\text{min}} \end{cases}
\]

(7)

Where, \( \lambda \) is the penalty coefficient, \( V_{\text{max}} \), \( V_{\text{min}} \) are respectively the maximum and minimum values of the voltage at node \( i \).

3.2. Equality constraints
Inequality constraints

\[
\begin{align*}
Q_{G_{\text{min}}} < Q_{G_i} &< Q_{G_{\text{max}}} \\
V_{\text{min}} < V_i &< V_{\text{max}} \\
Q_{G_{\text{min}}} < Q_{G_i} &< Q_{G_{\text{max}}} \\
V_{\text{min}} < V_i &< V_{\text{max}}
\end{align*}
\]

Where \( Q_{G_{\text{min}}} \) and \( Q_{G_{\text{max}}} \) are respectively the minimum and maximum value of the capacity of the shunt capacitor groups at node \( i \); \( Q_{G_{\text{min}}} \) and \( Q_{G_{\text{max}}} \) are respectively the minimum and maximum value of the DG reactive power output at node \( i \); \( V_{\text{min}} \) and \( V_{\text{max}} \) are respectively the minimum and maximum value of the voltage amplitude at node \( i \).

4. The procedure of the voltage optimization control based on the PSO

We solve the model which is established in Section Three by using the PSO. PSO is an artificial intelligent algorithm that can be applied to solve the optimization problems efficiently.

Particle swarm optimization initializes a group of random particles first, and then finds the optimal solution through iteration. The particles track two extreme values which are the individual extreme value \( p_{\text{Best}} \) and the global extreme value \( g_{\text{Best}} \) to update their velocity and position.

The procedure of the voltage optimization control is shown as follows:

Step 1: Enter the relevant parameters for the study, including load data, the limits of the voltage, the numbers and range of control variables. The number of the control variables has been reduced through the determination of the key nodes in the Section Two.

Step 2: Set parameters of the algorithm which includes particle population size \( N \), the number \( s \) of iteration \( T \), the acceleration coefficient \( c_1, c_2 \), and so on.

Step 3: Randomly initialize the particle swarm, generating the position and velocity of each particle. Then calculate power flow and evaluate the fitness for each particle. The current position of each particle is taken as the optimal solution \( p_{\text{Best}} \) of the particle. Among all \( p_{\text{Best}} \), the best one is set as \( g_{\text{Best}} \).

Step 4: Update the position and speed of the particles and calculate power flow again, then we can get the fitness of each particle. If the current fitness is greater than the previous extreme value \( p_{\text{Best}} \), it is assigned as \( p_{\text{Best}} \). If the best extreme value \( p_{\text{Best}} \) is greater than the previous global extreme value \( g_{\text{Best}} \), it is assigned as \( g_{\text{Best}} \).

Step 5: If the maximum iteration number is reached, then stop. Otherwise, continue from Step 3.

Step 6: Output the results.

5. Case study

5.1. Testing system

The IEEE 33-bus distribution network whose rate voltage is 12.66 kV includes 33 nodes. The system data can be found in [6]. For this study, we use the improved IEEE-33 bus distribution system as the test system. There are three 500 kW DG which are connected to the node 5, node 11 and node 26,
respectively. It is considered that each DG can control the voltage, and the range of the reactive power output is from -300 to 300 kvar. Shunt capacitors are installed at node 4, 7, 11, 13, 17, 19, 28. Each node is equipped with 10 groups of shunt capacitors, and the capacity of each group is 100 kvar. The voltage range is set to [0.95, 1.05] pu. PSO parameters are set as follows: particle population size \( N = 20 \), the number of iterations \( T = 100 \), the acceleration coefficients \( c_1 = c_2 = 1.5 \).

According to the formula (4), we can get the orders of the nodes where shunt capacitors are installed as listed in Table 1.

**Table 1.** Orders of the nodes where shunt capacitors are installed.

| Node | key node contribution degree |
|------|-----------------------------|
| 4    | 0.03130                     |
| 7    | 0.03036                     |
| 28   | 0.03025                     |
| 19   | 0.03005                     |
| 11   | 0.02894                     |
| 13   | 0.02802                     |
| 17   | 0.02666                     |

Selecting the top 3 nodes from the Table 1, that is, the node 4, 7, 28 are the key nodes in this case. Then we bring them into the particle swarm algorithm to solve the model.

There are two schemes to simulate as follows:

- Scheme1: The distributed generators participate in voltage control.
- Scheme2: The distributed generators don't participate in voltage control.

Figure 1 and Table 2 show the simulation results.

**Figure 1.** Node voltage curve.

**Table 2.** The results of voltage control.

|                   | Capacitor switching groups | DG reactive power output /kW | Power loss/kW |
|-------------------|----------------------------|-------------------------------|---------------|
|                   | (4/7/28)                   | (5/11/26)                     |               |
| Scheme 1          | 4/2/10                     | 39/300/21                     | 57.3337       |
| Scheme 2          | 5/6/9                      | 0                             | 59.5194       |
| Before Optimization| 0                          | 0                             | 113.2797      |
5.2. Analysis of the simulation results
From the Figure 1, we can see that the node voltages are kept within the range allowed, and the voltage curve is improved obviously. It is shown that the voltage optimization control in the active distribution network can be realized well according to the method proposed in this paper. When the DG is connected to the network passively, and does not participate in voltage control, the voltage quality decreases. Table 2 shows that DG which participates in voltage regulation make the number of capacitors reduce and the power loss is also reduced slightly. It makes full use of the capacity of the DG, reducing the number of the switching capacitors. It shows that reactive power compensation equipments coordinated with DG in the active distribution network to realize the voltage control can obtain the better results.

Conclusions
This paper proposes a novel way to realize the reactive power and voltage optimization control. Combined with the theories of complex networks, the key node contribution degree is defined to determine the key nodes. The PSO is applied to solve the model with fast convergence speed and satisfactory results. The method presented in this paper reduces the range of voltage regulation, making the voltage regulation more directional. The simulation results of the case show that the proposed method can solve the problems of the voltage limit violation, reduce the power loss and improve the voltage stability significantly. It also can be seen that DG actively participates in the voltage control can improve the voltage level effectively.

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