A Distributed Voltage Control Method Based on Local Sensitivity Information for Incremental Distribution Network

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Abstract. The access of the distributed generator supply provides a supportive effect for the node voltage in the active distribution network, but at the same time also reduces the stability of the distribution network. The algorithm establishes the sensitivity matrix and analyzes the relationship between the node voltage and the reactive power output, to coordinating the output of each reactive power. Since the undervoltage and overvoltage of different nodes can be present in the network at the same time, the overvoltage and undervoltage can be adjusted, which achieve the control of the network node voltage. The simulation results show that the algorithm can realize the effective return of the node voltage and increase the stability of the distribution network voltage.

Keywords: Distributed generator, Distribution network, Sensitivity matrix

1. Introduction

In recent years, with the rapid development of new energy, electric vehicles and other industries, the increasing number of distributed generations (DGs) access has brought more volatility and uncertainty to the distribution network, which poses new challenges to the network planning, construction and operation management of the distribution network [1,2]. The proposal of Active Distribution Network (ADN) provides an opportunity to solve the above problems [3-5]. In ADN, the coordination among DG, loads and equipment is very important, which is related to the security and operation efficiency of the system [6]. It all depends on the reasonable grid structure and control methods. The control method of distribution network power flow depends on the structure of the communication network. The development of measurement technology makes it possible to install accurate measurement information equipment (RTU) in every equipment of power system. The power flow information of each node can realize real-time communication, which provides basic technical support for the management and control of ADN [7-9].

At present, there are three main control modes of ADN: centralized, distributed and hybrid. The centralized control mode uses RTU to send all DGs information to the central controller, which integrates data and regulates the network. Different from centralized control, distributed control avoids centralized data processing by central controller, but uses multiple local controllers to control, and the number of power supply is not limited [10,11]. If the power flow of the system needs to be adjusted,
each node only exchanges information with its adjacent nodes and iterates. Finally, the active or reactive power required by each distributed device is obtained to control the whole system [12]. In this paper, a distributed voltage control method based on local sensitivity information is proposed on the basis of distributed control mode of ADN. It can adjust the reactive power-voltage sensitivity of nodes to change the reactive power output, and realize the direct or indirect impact on the node voltage. At the same time, undervoltage and overvoltage are adjusted simultaneously to keep voltage value maintained in the normal range. This method is more accurate compared with sag control.

2. Network Structure

2.1. A subsection

The goal of distribution network voltage control is to control the system voltage within a safe operating range and reduce operating costs as much as possible. The communication framework of distributed control mode is shown in Figure 1. Among them, PEDG represents the DGs connected to the network through the inverter interface, PEC represents the power electronic conversion device, ESS represents the energy storage device, LC represents the local controller. From the figure, it can be seen that in the distributed control network, each controllable device is connected with a local controller, and the local controllers communicate with each other through communication lines.

![Figure 1. Distributed Control Communication Framework.](image)

2.2. Network Topology

In order to facilitate the description, the related concepts of graph theory are introduced to represent the connection relationship of nodes in distribution network. Graph \( G = (V, E) \) is used to represent the information interaction relationship between nodes. Where \( V = \{1,2,..., N\} \) is a node set representing the communication line between node \( i \) and node \( j \). Define all neighbor nodes with \( i \) as the end points, which are called node \( j \).

2.3. General Derivation of Distributed Algorithms

\( x_i^{(k)} \) represents the value of node \( i \) in the \( k \)th node information exchange process. The distributed algorithm is described as follows: in the \( k \)th iteration, node \( i \) updates its value based on the current value \( x_i^{(k)} \) of node \( i \) and the current value of neighbor node \( j \) of node \( i \):

\[
x_i^{(k+1)} = a_i x_i^{(k)} + \sum_{j \in N_i} a_{ij} x_j^{(k)}
\]

(1)

Where \( a_i \) represents the ratio of node \( i \) to keep its own value in the \( k \)th iteration; \( a_{ij} \) represents the ratio of the value transferred from node \( j \) to node \( i \) in the \( k \)th iteration, so we can know that the range of \( a_{ij} \) is \([0,1]\). A matrix \( A \) consisting of proportional value \( a \) is essentially a weight matrix and a column random matrix. The sum of each column is 1, so the formula can be expressed as

\[
x^{(k+1)} = Ax^{(k)}
\]

(2)
According to document [13], the structure shown in formula (2) is similar to Markov chain, and matrix $A$ is called state transition matrix. According to the nature of Markov chain, if the state transition matrix $A$ is both a column random matrix and a primitive matrix [14-18], then formula (2) has a unique stationary distribution $x$, which makes the algorithm convergent. The convergence condition of the algorithm is demonstrated in document [13].

By updating the weight matrix $A$ to update the value of $x$ continuously, the convergent steady-state solution is obtained and the distributed algorithm is realized.

3. A Distributed Algorithm Based on Local Reactive Power Sensitivity Information was Developed
In power system, the relationship between power change and bus voltage and phase angle is shown in equation.

$$
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} = 
\begin{bmatrix}
H & N \\
K & L
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
\Delta U
\end{bmatrix}
$$

(3)

Transform Formula (3) to get

$$
\Delta U = C \cdot \Delta P + F \cdot \Delta Q
$$

(4)

In formula (4), $C$ is active power sensitivity matrix and $F$ is reactive power sensitivity matrix. Reactive power flow in power system is mainly related to the voltage amplitude of each node, and ADN requires maximum distributed energy utilization, so $P=0$, then $\Delta U$ can be calculated as:

$$
\Delta U = F \cdot \Delta Q
$$

(5)

3.1 Distributed Control Based on Local Sensitivity Information
According to the previous analysis, the distributed voltage control of the distribution network based on local sensitivity information refers to the process of realizing the total incremental reactive power distribution through reactive power generation devices connected to the nodes, such as DGs, and controlling node voltage of DGs by adjusting the reactive power. In the process of distribution, DGs with reactive power generation capability and reactive power compensation equipment are regarded as reactive power source. Assuming that the distribution network has $n$ nodes, according to the distributed algorithm, the updating rule of $Q$ is as follows:

$$
\Delta Q^{(k+1)} = D^{(k)} \cdot \Delta Q^{(k)}
$$

(6)

Among them, $\Delta Q^{(k)}$ is n-dimensional vector, and partial weight matrix $D^{(k)}$ is n-dimensional state transition matrix based on distribution network communication network topology. The algorithm continuously modifies the reactive power-voltage sensitivity matrix $D^{(k)}$ iteratively to ensure that the power distribution results meet the voltage limitation and DG output limitation.

According to the communication structure diagram of active distribution network, the simplest case is that power lines realize the transmission of information between adjacent nodes and bidirectional communication, then every node transmits information with its neighbor nodes. One node can not obtain global information and use local sensitivity information to adjust reactive power variation to control voltage. The network structure is represented by the reactive power-voltage sensitivity matrix $D^{(k)}$ and the elements in the matrix are represented by the edge $D_{ij}$ of the structure graph. The relationship between reactive power change and voltage change is reflected by sensitivity coefficient $\beta$. The value of $\beta$ is shown in formula (7):

$$
\beta_j = \frac{\partial U_i}{\partial \Delta Q_j}
$$

(7)

Where node $j$ is the neighbor node of node $i$, the size of $d_{ij}$ equals the sensitivity of node $j$. If not, it changes to 0 to reflect the flow object of local information.
Based on the convergence requirement of the distributed algorithm, when updating the weight matrix \( D_{ik} \), it should always be kept as a diagonal matrix. Therefore, it is necessary to diagonalize the matrix \( D_{ik} \) to run the algorithm.

The core purpose of distributed voltage control based on local sensitivity information is to estimate the reactive power that DG needs to increase or decrease when grid voltage is beyond the limit, and distribute the distributed power variation among DGs by updating the weight matrix \( G^{(k)} \). The updating rules of the weight matrix are as follows:

\[
D^{(k+1)} = DG^{(k+1)} + (I - G^{(k+1)})
\]  
(8)

\[
G^{(k)} = diag(\omega_1^{(k)}, \omega_2^{(k)}, ..., \omega_n^{(k)})
\]  
(9)

Among them, matrix \( G^{(k)} \) is the parametric diagonalization matrix, whose parameters satisfy \( 0 < \omega_i \leq 1 \), and \( I \) is the n-dimensional unit diagonal matrix. Each iteration updates the parameter \( \omega_i \) according to the requirement of voltage adjustment and DG capacity limitation. Its size is determined by the voltage ratio of node \( i \), and the value of \( i \) is related to the increase or decrease of DGs output at node \( i \).

In the first \( k/2 \) iterations, \( i \) is modified according to each voltage estimate. If \( U_i' \) is known to be the node \( i \) voltage value calculated by power flow at \( r \), then the voltage of node \( i \) at \( r+1 \) can be estimated as:

\[
\rho_i = U_i' + \Delta U_i'
\]  
(11)

The rated voltage of \( U_i \) is 1. If the voltage value of node \( i \) is low, \( \rho_i \leq 1 \). In the next iteration, \( \omega_j^{(k)} \) needs to be reduced to increase the reactive power output of reactive power generating equipment. In turn, \( \rho_i > 1 \), and the increase of \( \delta_i^{(k)} \) is needed to reduce. The updating rules for parameter \( i \) are as follows:

\[
\omega_i^{(k+1)} = \begin{cases} 
\omega_i^{(k)} & \rho_i^{(k)} \leq 1 \\
\rho_i^{(k)} & \rho_i^{(k)} > 1
\end{cases}
\]  
(12)

In the latter \( k/2 \) iteration, the capacity limitation of reactive power generation equipment will be considered. If the power distribution results meet the power limitation, there is no need to modify \( D^{(k)} \). When the reactive power demand is greater than \( Q_{max} \), \( Q \) equals \( Q_{max} \); when the reactive power demand is less than \( Q_{min} \), \( Q \) equals \( Q_{min} \). Then other nodes redistribute power.

In the same way, the updating rules of parameters under overvoltage are deduced. Undervoltage and overvoltage may occur in different areas of distribution network. The final calculation results are obtained by combining the two algorithms.

### 4. Case Study

In order to verify the effectiveness of the distributed voltage control algorithm, an example of IEEE standard 33-bus distribution is analyzed. The bus voltage of the system is 12.66 kV. The lower limit of voltage safety is 0.968, and the upper limit of voltage safety is 1.045. The load and branch impedance of all nodes are referred to in reference [11].

When DGs are not connected, the voltage of most nodes is lower than the lower limit of voltage safety. The voltage curve of nodes is shown in Figure 2. DGs are connected to nodes 5, 13, 15, 20 and 23. The capacity of DGs is 1200+j580 kVA. The continuous reactive power regulator is connected to nodes 29. DGs play a supporting role in the voltage of distribution network nodes, which makes the voltage of all nodes higher than the lower limit of safety voltage. At the same time, due to the access of DG, the voltage of some nodes is higher than the upper limit of safety voltage. After DG is connected, the voltage of nodes is divided into several parts. The distribution curve is shown in Figure 3.
Figure 2. Nodes Voltage Distribution without DG. Figure 3. Nodes Voltage Distribution with DG.

After DGs are connected, the voltage of some nodes exceeds the upper limit. It can be seen from the analysis of distributed algorithm that the reactive power output value of DGs need to be reduced when overvoltage occurs. The distribution of nodes voltage after DGs regulated by algorithm is shown in Figure. 4. And the relationship between nodes voltage and iterations is shown in Figure. 5. The reactive power generated by nodes after algorithm adjustment is shown in Table. 1.

Figure 4. Nodes voltage after DGs regulated. Figure 5. Voltage results after adjustment.

| Nodes | Reactive Power    |
|-------|-------------------|
| 5     | 741+323j          |
| 13    | 668+327j          |
| 15    | 761+360j          |
| 20    | 1200+580j         |
| 23    | 1200+580j         |
| 29    | 298               |

For example, during the adjustment process, DG carried by node 15 can not be connected to distribution network due to faults or maintenance reasons. The distribution of voltage in the distribution network is shown in Fig. 6.

Figure 6. Voltage distribution of DG not connected to power grid in node 5. Figure 7. Control results (excluding DG with node 15).
The algorithm continues to adjust. As shown in Fig. 7, the voltage of all nodes is within the allowable range. The voltage variation of nodes in the number of iterations is shown in Fig. 8.

![Figure 8. Iterative results of the algorithm.](image)

| Table 2. Reactive power output of each DG node (excluding DG with node 15). |
|------------------|------------------|
| Nodes           | Reactive Power   |
| 5               | 1200+580j        |
| 13              | 1012+493j        |
| 20              | 1200+580j        |
| 23              | 1200+580j        |
| 29              | 389              |

5. Conclusion
In ADN, when the output power of DGs can be adjusted, the voltage of each node in the distribution network can be adjusted by controlling the reactive output of DGs. Distributed algorithm based on local sensitivity information regulates the voltage of each node by controlling the reactive power output of reactive power output equipment in distribution network. According to bus voltage and the capacitance of each reactive power equipment, the reactive power of each reactive power equipment is adjusted according to the node voltage situation. By changing the sensitivity matrix, the reactive power of each reactive power equipment is iterated several times, and finally the requirements are met. This distributed control method does not require access to the central controller, which reduces the computational complexity and processing pressure of the system. At the same time, because all communication links are distributed in the distribution network, when part of the network structure is damaged, it may affect the voltage stability of the whole network. Therefore, further improvements can be made in the network topology results and redundant branches can be added to enhance the stability of distribution network communication structure.

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