Voltage Adjustment of Distribution Network Including Distributed Power Based on Wide Area Information

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ABSTRACT: With the access of distributed generator, it changes the trend of the distribution network flow and voltage distribution. And the output power of the DG has the characteristics of randomness and interval, which can affect the control strategy of the transformer substation. In order to improve the influence of the distributed power on voltage, in this paper, based on the typical chain-shaped radiative distribution network, the influence of voltage distribution after the access of distributed generator is studied. On this basis, a coordinated control strategy based on wide-area information "bus voltage priority regulation, distributed power supply coordination regulation" is proposed, which takes full-line voltage reaching the standard as the optimization goal. Through the simulation of the improved IEEE 33-node distribution network, it is verified that the coordinated control strategy can effectively improve the power quality of the distribution network, and control the voltage deviation within the allowed range.

1. Introduction
Distributed Generation (DG) has the advantages of high power supply quality, high reliability and good environmental benefits, which enables it to develop rapidly and become a new research hotspot of power system. However, with the continuous access of DG, the reliability of distribution network [1], power flow distribution [2], relay protection [3][4] and so on, will be greatly affected. A lot of research work has been done to optimize the access location and capacity of DG. Literature [5] and literature [6] studied the influence of DG on the voltage distribution of distribution network and the limitations of distributed power supply injection capacity and access location. Literature [7] discussed the limitations of DG type, location and capacity from the perspective of system power loss. Literature [8] summarized the voltage control strategy after the DG accessed to the grid.

For power customers, the power supply quality must be guaranteed and the grid voltage stability within the specified range is the primary concern. GB12325-2008"The Allowable Deviation of Power Supply Voltage" specifies clearly the voltage deviation of different voltage levels [9]: the voltage deviation of three-phase power supply of 10kV and below voltage levels is between -7% and 7%. Traditional distribution network uses the voltage and reactive power integrated control (VQC), substation voltage regulation is implemented by the on-load tap-changing transformer (OLTC). But this way of regulating only guarantees the voltages of bus bar within the acceptability limit, it can't guarantee the voltages of distribution network within the acceptability limit. And with the permeability of DG increasing, the access or exit of DGs may cause low voltage or high voltage [10-12].
According to the comprehensive analysis of the above references, the topological structure change of the actual distribution network is not taken into account, the intermittency, randomness and output instability of the DGs are not considered, and the fluctuation characteristics of the distribution network load are not considered. This paper presents a coordinated control strategy based on the principle of "bus voltage priority regulation and DG coordination regulation", and verifies the strategy through simulation of the improved IEEE33 node distribution network.

2. Influence of DG access to distribution network

The output of DG is unstable, which has the characteristics of random, intermittent, time-varying. With the access to distribution network, the DG can generate power and also absorb power; it changes the power flow direction and the voltage distribution. With the change of DG’s output and load fluctuations, it seriously influences the user’s electrical equipment; effective measures must be taken to solve the problem of voltage regulation.

Using matlab/simulink to build a radial chain distribution network simulation model as shown in Fig.1, there are 10 nodes on the feeder line, the distance between every two adjacent nodes is 1 km, uniform distribution load, load under the minimum operation mode, the total active power is 3 MW, power factor is 0.95, load under the largest operation mode, the total active power is 5 MW, power factor is 0.9, DG is accessed from the node 8, DG’s output is $P_{DG}=2\text{MW}$.

![Fig.1 Distribution network simulation model with DG](image)

As shown in Fig.2, for the distribution network with DG, if DG access or exit from the distribution network, combined with the change of load, it will lead to the following two situations:

![Fig.2 DG output fluctuation](image)

(a) Voltage distribution under light load  
(b) Voltage distribution under heavy load

1) When the feeder lines are lightly loaded, if DG has a large capacity to access the feeder lines, and the access position of DG is closer to the end of the feeder lines, it will cause that the bus bar voltage is qualified, but the voltage at the access node of DG is higher than the upper limit.

2) When the feeder lines are overloaded and the output of the DG decreases or exits the operation, it will cause that the bus bar voltage is qualified, but the end voltage of the line is lower.

The above simulation results show that after the DG is connected to the distribution network, the traditional substation control strategy can no longer meet the target of voltage regulation. Therefore, effective voltage regulation means must be adopted to coordinate the voltage regulation strategy of DG and the substation, so that the voltage across the whole line can meet the requirements.
3. Voltage regulation control strategy based on wide area information

In practice, the operation mode and structure of distribution network will change, so it is necessary to track and identify the topology structure. SCADA system can be used to collect real-time operation data such as operating voltage, reactive power and active power of all nodes in the whole network [13]. The overall structure of the system is shown in Fig.3. Distribution transformer supervisory terminal unit (TTU) is installed at the transformer. Feeder terminal unit (FTU) is installed at branch switch, section switch, contact switch, DG connection switch, etc. Distribute terminal unit (DTU) is installed in ring main units and switch stations. The collected data is transmitted to the master station through the communication network. The main decision control center calculates and analyzes the main data, and makes quick control strategy between substation and DG.

The principle diagram of the decision control center of the master station is shown in Fig.4, which is mainly composed of data acquisition module, network topology identification module, online calculation and analysis module, control strategy module and scheme execution module. Through the coordinated control of substation and DG output adjustment, the node voltages are tracked and fed back to constantly refresh the collected data.

Data acquisition module: Wide-area information is collected including the tap position of the main transformer and the number of switching groups of capacitor, connection switch status, node voltage, load, DG interconnection switch state and DG’s output, etc. And then transmit the data to the main station for storage at high speed through Ethernet Passive Optical Network (EPON).

Network topology identification module: The power network topology analysis method is used to analyze the data acquired by the data acquisition module. The power network topology analysis methods mainly include the adjacency matrix method [14-15] and tree search method [16-18]. In this paper, the power network topology analysis method is based on breadth first search proposed in literature [17], it can quickly identify the topology structure of the distribution network.

Online calculation and analysis module: This module quickly forms the node admittance matrix $Y_B$ of the distribution network according to the topological structure identification results; calculates the Jacobi matrix $J$; calculates the sensitivity $\Delta U$ of the node voltage $U$ to the node injection power, as shown in Eq. (1).
\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
J_a & J_b \\
J_j & J_k
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
\Delta U
\end{bmatrix}
\]

(1)

Control strategy module: The coordinated control strategy of “bus voltage priority regulation and DG coordination regulation” is adopted. The main steps are as follows:

1) Using sort algorithm ranks the node voltages of the distribution network. And the qualified range of voltage is the range \([0.93, 1.07]\), then search the maximum and minimum value of node voltages according to Eq. (2), and judge and determine the node \(k\) with the most serious out-of-limit. If \(U_{k1} < 0.93\), then \(k = k1\); and if \(U_{k2} > 1.07\), then \(k = k2\).

\[
\begin{align*}
U_{k1} &= \min(U_i, i=1,2,...n) \\
U_{k2} &= \max(U_i, i=1,2,...n)
\end{align*}
\]

(2)

Where, \(U_i\) is the voltage of node \(i\); \(n\) is the number of nodes; \(U_{k1}\) is the minimum node voltage value; \(U_{k2}\) is the maximum node voltage value;

2) Search the DG’s access node \(d\) that is closest to the node \(k\) according to the network topology;

3) According to VQC, give priority to adjust the taps of OLTC, switch and cut of capacitor groups to ensure that the voltage of substation bus bar is qualified;

4) According to the voltage sensitivity \(\Delta U\) calculates the output active power \(\Delta P_{DG}\) and reactive power \(\Delta Q_{DG}\) of the DG at node \(d\) from Eq. (1), to make the node \(k\) voltage qualified;

5) According to the adjustment amount calculated in Step 4), judge the adjustment range, if \(\Delta P_{DG} > 0\) or \(\Delta Q_{DG} > 0\) means that DG needs to increase its output, and \(\Delta P_{DG} < 0\) or \(\Delta Q_{DG} < 0\) means that DG needs to reduce its output:

a) If the voltage is higher than the upper limit, the DG at node \(d\) needs to reduce its output. If \(P_{DG} + \Delta P_{DG} < 0\), then jump to step 3), and adjust the tap of the OLTC, reduce the bus bar voltage. Otherwise, the DG at the node \(d\) adjusts its output according to the calculated adjustment amount \(\Delta P_{DG}\) and \(\Delta Q_{DG}\);

b) If the voltage is lower than the lower limit, the DG at node \(d\) needs to increase its output. If \(P_{DG} + \Delta P_{DG} > P_{max}\) (P\(_{max}\) is the maximum output of DG), then turn to step 3) adjust the tap of OLTC, to increase the bus bar voltage. Otherwise, the DG at the node \(d\) adjusts its output according to the calculated adjustment amount \(\Delta P_{DG}\) and \(\Delta Q_{DG}\);

6) Collecting the data, dynamically updating the adjusted information, and turn to Step 1) until the voltage of all nodes of the line is qualified.

4. Simulation analysis

The improved IEEE33 nodes distribution network is used as the simulation example. The IEEE 33 nodes distribution network has 33 nodes, 32 branches, six contact switches: S1-S6, the dotted line as shown in Fig.8. The rated voltage is 12.66 kV, the total load is 3715 kW + j2240kvar, benchmark capacity is 10 MVA, the qualified range of node voltage using per-unit(pu) value set as \([0.93, 1.07]\), DGs are connected at nodes 21, 24, 31, 10 and 16. The network structure is shown in Fig.5.

Fig.5 Improved IEEE 33 node distribution system diagram

Access location and capacity of DGs are shown in Table 1.
Table 1 Access location and capacity of DG

| Serial number | Access location | Rated capacity $P_{DG}$/kW |
|---------------|----------------|----------------------------|
| DG1           | 21             | 400                        |
| DG2           | 24             | 120                        |
| DG3           | 10             | 150                        |
| DG4           | 31             | 400                        |
| DG5           | 16             | 300                        |

Example 1: In this case, switch S1 is closed, and switch S2 - S6 is disconnected, DG4’s output power is 50% of rated capacity, the rest of the DGs produce power at their rated capacity. The wide area information is used to collect the information of distribution network, and the topology structure is identified. According to the topology structure identification results of distribution network, the node admittance matrix $Y_B$ of distribution network is quickly formed, and Jacobi matrix $J$ is calculated. The voltage value of node 33 is the lowest that can be obtained through simulation search, its value $U_{33}$ is 0.9291 (pu). The voltage deviation value $\Delta U_{33}$ is 0.0009.

The closest DG to node 33 is found to be DG4. According to formula (2), the output adjustment amount $\Delta P_{DG4}$ is 61.015kW. When DG4 increases its output of 61.015kW, the voltage value $U_{33}$ of node 33 is 0.93001 and the rest node voltage of all distribution network are qualified. The simulation results are shown in Fig.6.

![Fig.6 The result before and after voltage adjustment of exam one](image)

Example 2: The load data of IEEE33 nodes distribution network is adjusted to be heavy load, the total load is 5600 kW + j3260kvar. The tap of OLTC is adjusted so that the voltage unit value at the bus bar is 1, switch S1 is closed, and switch S2 - S6 is disconnected, all DGs produce power at their rated capacity. Just like in example 1, the topology structure is identified, the node admittance matrix $Y_B$ of distribution network is quickly formed, and Jacobi matrix $J$ is calculated. The voltage value of node 33 is the lowest that can be obtained through simulation search, its value $U_{33}$ is 0.8653 (pu). The voltage deviation value $\Delta U_{33}$ is 0.0647.

The closest DG to node 33 is found to be DG4. According to formula (2), the output adjustment amount $\Delta P_{DG4}$ is 98.152kW. When DG4 increases its output of 98.152kW, the voltage value $U_{33}$ of node 33 is 0.93001, but DG4 produces power at rated capacity, so DG4 can’t increase output. According to the coordinated control strategy of this paper, adjusting the tap of OLTC makes that the bus voltage is 1.05, and all node voltage of the distribution network is qualified. The simulation results are shown in Fig.7.
5. Conclusions
In this paper, based on the typical chain-like radiative distribution network, matlab/simulink is used to simulate and analyze the influence of DG on the voltage distribution of feeder lines. Based on the above analyses, this paper puts forward a coordinated control strategy which is "bus voltage priority regulation and DG coordination regulation" based on the wide-area information. The coordinated control strategy makes full use of the advantages that DG is flexible access, and is easy to adjust its output power. This strategy takes all node voltage reaching the standard as the optimization goal, uses wide area information to obtain the voltage of each node in the distribution network; DG's output, access position and power factor; the states of the interconnection switch; load on feeder branches, etc. The breadth first search algorithm is used to quickly complete the topology identification of the distribution network, and then the optimal control strategy is obtained by the calculation and analysis. After the implementation of the optimal control strategy, data collection is carried out to track the adjusted node voltage, which forms a closed-loop control and adjustment, until the voltage of all nodes of the line is qualified. The effectiveness and feasibility of the proposed strategy are verified by the improved IEEE33 node simulation.

Acknowledgments
This study was supported by the Scientific Research Fund of Education Department of Yunnan Province.

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