Reactive power optimization system of distribution network based on edge calculation

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Abstract: To deal with the adjustment difficulties caused by the access of photovoltaic (PV) in distribution network, this paper introduces a reactive power optimization system of distribution network based on edge calculation. The proposed system includes two parts. Firstly, the distribution PV edge nodes based on edge calculation are carefully designed. Secondly, based on the edge nodes, the PV station, the grid reactive power optimization, the Automatic Voltage Control (AVC) centre, and the distribution photovoltaic power reactive voltage are co-ordinately controlled. The simulation results prove that the proposed system can effectively improve the voltage quality and the voltage regulation ability of distribution network.

Keywords: Distributed photovoltaic; Edge calculation; Edge node; Reactive power optimization of distribution network; PV inverter

1. Introduction
In recent years, more attention has been paid to the clean energy to deal with energy depletion and environmental pollution. As a result, the distributed photovoltaics have been widely used in power systems. However, the access of distributed photovoltaics will lead to the voltage fluctuation and increase the risk of contingencies in the distribution network. So it is very important to study the reactive power voltage optimization strategy of the distribution network with multi-distributed photovoltaic access.

Generally, the centralized control method and the in-place control method are used for the control of PV in distribution network. Reference [1] studies the change of node voltages caused by the access of PV and proposes a voltage optimization method based on the forecast model. Reference [2] establishes a multi-object optimization model including the access of wind generation and PV and finds the Pareto optimization results of this model based on Monte-Carlo method and Chance Constrained programming method. Reference [3] introduces the virtual injection power to simplify the control model based on the voltage sensitivity. Reference [4] researches the static reactive power optimization for distribution network including DG and proposes the optimal adjustment method of balance partition based on the dynamic range of node compensation capacity. References [5]-[7] proposes the mixed reactive power optimization method including distributed photovoltaics, the two stages optimization method including heuristic search and variables correction, and the dynamic reactive power optimization method based on second order conic programming, respectively. Reference [8]
studies the strategy of PV voltage in-place control. Reference [9] researches three in-place control models of QV, PF, and APC. The most widely used in-place control method is vertical descend method [10]. References [11]-[12] propose that above centralized methods ignore the fast adjustment ability of PV inverter and the in-place methods ignore the coordination. Because of the difficult communication, most of distributed PV stations are kept from the overall reactive power control [13]. In fact, many advanced control methods are not applied in actual distribution network.

Edge calculation (EC) is a new model which includes the collection, real-time process, and analysis of local data. It can reduce the communication with network centre, so that the response speed will be greatly improved [14]-[15]. According to [16], EC is appropriate for distribution network. At present, some application researches have a good performance in the fault handling and virtual power plant of actual power system [17]-[18].

As mentioned above, this paper proposes the reactive power optimization system of distribution network based on edge calculation, in which the reactive power control of distributed PV is realized by EC. The proposed system includes two parts. Firstly, the distribution PV edge nodes based on edge calculation are carefully designed. Secondly, based on the edge nodes, the PV station, the grid reactive power optimization, the Automatic Voltage Control (AVC) centre, and the distribution photovoltaic power reactive voltage are controlled co-ordinately. In this way, the advantages of both centralized method and in-place method are combined. The overall optimization control is realized and the communication with control centre is greatly reduced. Besides, the system is convenient to be expanded and can afford the access of large-scale distributed renewable energy.

2. Design of Edge Photovoltaic Nodes

The photovoltaic edge nodes are placed in the end of distributed photovoltaic station network. In this way, the distribution network centre can participate in the coordinated optimization control of the entire network through wireless communication while the station's centralized network port, the information acquisition system, the photovoltaic inverters, energy storage devices, and the reactive power compensation equipment can communicate with each other in time.

2.1. Definition of edge photovoltaic nodes

Photovoltaic edge nodes are responsible for the data analysis, strategy calculation, and equipment control in the centre PV station. The AVC co-ordinately control the whole network with the PV edge nodes. Besides, the regulation capability of distributed PV station is utilized through the PV edge nodes.

2.1.1. Function of PV edge nodes

The PV edge nodes receive the coordinated instruction from the distribution network centre, so that the PV line models and real-time data can be combined to complete the reactive power optimization control.

Therefore, the function of edge PV nodes are as follows: 1) Network modelling: including PV inverters, energy storage devices, reactive power compensation equipment, switch switches, etc., 2) Data collection: real-time collection of key voltage and reactive power data, 3) Edge node reactive power adjustment capability calculation: calculate and update the edge node real-time reactive power adjustment capability according to the formula in 2.1.3, 4) Coordination: send coordinated control variables to the centre of the distribution master station and receive the distribution master station real-time collaborative control instructions, 5) Strategy calculation: according to the coordinated instruction issued by the master station, the reactive power optimization strategy calculation of the PV edge node is completed and the control instruction is generated, and 6) Control: send control commands to the equipment to complete closed-loop control.

2.1.2. In-place control mode of PV edge nodes

The automatic control of power requires all-weather control, covering both normal and abnormal conditions. In addition to the normal mode functions in 2.1.1, the PV edge node also designs an in-place control mode. When an abnormality occurs in real-
time collaboration, the edge nodes automatically switch to in-place control, in which the pre-designed gateway voltage assessment is the main goal to realize the in-place automatic voltage control calculation, and the influence of the coordinated variables is not considered.

2.1.3. Adjustment capacity calculation of edge nodes. The adjustment capacity calculation of edge nodes is derived as follows. When the active output of the inverter in PV station is lower than the maximum output, we can not only reduce the active power but also immediately increase the reactive power. The specific adjustable reactive power can be calculated by the following formulas:

$$Q_{PV}^{Max} = +\sqrt{S_{INV}^2 - P_{PV}^2}$$

(1)

$$Q_{PV}^{Min} = -\sqrt{S_{INV}^2 - P_{PV}^2}$$

(2)

where $Q_{PV}^{Min}$ and $Q_{PV}^{Max}$ are the minimum and maximum reactive power output of PV inverter. $S_{INV}$ is the maximum active power output. $P_{PV}$ is the real-time active power output.

Theoretically, the maximum reactive power output of PV edge nodes is the total adjustable reactive power ranges of all photovoltaic inverters, so that the reactive power output in PV nodes are calculated as follows:

$$Q_{E}^{Max} = \sum_{i=1}^{n} Q_{PV}^{Max} = +\sum_{i=1}^{n} \sqrt{S_{INV}^2 - P_{PV}^2}$$

(3)

$$Q_{E}^{Min} = \sum_{i=1}^{n} Q_{PV}^{Min} = -\sum_{i=1}^{n} \sqrt{S_{INV}^2 - P_{PV}^2}$$

(4)

where $n$ is the set of all inverters in PV station.

When the edge nodes include other discrete reactive power compensation equipment, the final reactive power output capacity of the PV node is:

$$Q_{E}^{Max} = \sum_{i=1}^{n} \sqrt{S_{INV}^2 - P_{PV}^2} + \sum_{j=m} Q_{Cj}$$

(5)

$$Q_{E}^{Min} = -\sum_{i=1}^{n} \sqrt{S_{INV}^2 - P_{PV}^2} - \sum_{l=m} Q_{Cl}$$

(6)

where $m$ is the set of discrete reactive power compensation equipment which are not in operation. $Q_{Cj}$ is the available capacity of equipment $j$ which are not in operation.

According to above discussion, after the data of local inverters and compensation equipment are obtained, the adjustment capacity of this node can be calculated and uploaded.

2.2. Configure edge nodes based on grid standard architecture

After the calculation and communication functions are determined in last subsection, the PV edge nodes are configured according to the IEC62939 standard in the field of smart grid user interface. The edge node architecture in the IEC62939 standard includes a basic platform, a functional layer, an information layer, and a communication layer. According to the layered architecture, PV edge nodes are defined and configured in Table 1.

2.3. Edge Nodes Data Processing and Calculation

The core functions of edge nodes are the periodic and strategy calculation of PV node real-time reactive power regulation capability. Generally, the grid connection points are regarded as the boundary, the PV surrounding power grids are modelled, and the relevant real-time data are collected, so that the information can be combined in strategy calculation and the real-time control of equipment...
can be completed. To clarify above opinions, the strategy calculation process of reactive voltage in edge nodes is presented in Figure 1.

| Table 1. Hierarchical comparison table of photovoltaic nodes based on edge computing |
|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Standard layered                | Function                          | Function of PV nodes              | Hardware Configure               |
| Functional                      | Analysis and function              | User interaction, data           | Human-computer interaction display|
| Information                      | calculation, user interface (UI)   | processing, and calculation      | AC sampling board, binary input   |
| Information                      | Collect information               | Internal information interaction  | control logic board, etc.         |
| Communication                    | and control                       | and remote control               | Communication interface board,    |
| Communication                    | Standard interface,               | Analysis of letter               | wireless communication            |
| Communication                    | communication protocol             | acquisition protocol,            | communication module              |
| Basic platform                   | Public platform, dedicated platform| Provide development platform     | Embedded CPU, memory card, power  |
|                                 |                                   |                                 | supply, etc.                      |

![Figure 1. PV edge node algorithm](image)

3. Reactive power optimization control system of distribution network based on EC

In the distribution network, the reactive power optimization control process includes three technologies: 1) edge node data collection and processing, 2) distribution network centre reactive power optimization, and 3) edge node strategy calculation.

3.1. Edge nodes data collection and processing
Firstly, the edge nodes collect the power measurement of the PV station and the related equipment. Secondly, the status and adjustment capabilities of the local equipment are analysed according to the collected power measurement and node parameters. Finally, the status and adjustment capabilities of this node are obtained and uploaded to the distribution network centre.

3.2. Distribution network center reactive power optimization
The distribution network centre collects real-time data of the entire network including edge nodes, performs optimization calculations on the entire network, and gives the instructions for optimization adjustment.

3.3. Edge nodes strategy calculation
The edge nodes receive the adjustment instructions, combine local collected data with device parameters to perform local strategy calculations, and issue adjustment instructions to the controllable devices in the edge nodes.

3.3.1. Architect of EC based reactive voltage control system

The overall architecture of the system consists of the distribution network centre, distributed PV edge nodes, PV stations, peripheral control equipment, conventional distribution network substations, lines, and other direct control equipment.

3.3.2. Optimization model of EC based distribution network. The distribution network loss is dominated by line loss, accounting for more than 70%. Therefore, the reactive power optimization of the distribution network is mainly to minimize the network loss:

$$\min J = \sum_{i=1}^{N} P_{\text{loss}} = \sum_{i=1}^{N} [(\tilde{I}_{LR})^2 * R_{LR}]$$

(7)

where $P_{\text{loss}}$ is the line loss in power system, $N$ is the number of nodes in power system, $\tilde{I}_{LR}$ is the current injection of node $i$, $R_{LR}$ is the equivalent resistance of node $i$.

In the original distribution network model, adding a PV edge node as a virtual adjustable continuous reactive power source, and using the reactive power output capacity calculated by the edge node in real time as the adjustment capacity. Then the following constraints can be obtained.

1) Power balance
The power flow should satisfy the load requirement in each period.

2) Node voltages constraints

$$V_{i}^{\text{min}} \leq V_{i} \leq V_{i}^{\text{max}} \quad i = 1...N_{PQ}$$

(8)
where $v_{i}^{\text{min}}$ and $v_{i}^{\text{max}}$ are the minimum and maximum voltage limits of node $i$, respectively.

3) Capacitive reactance device constraints

$$Q_{c,i}^{\text{min}} \leq Q_{c,i} \leq Q_{c,i}^{\text{max}} \quad i = 1...N_c$$

4) Adjustable transformer constraints:

$$T_{k,i}^{\text{min}} \leq T_{k,i} \leq T_{k,i}^{\text{max}} \quad i = 1...N_T$$

5) Output constraints of PV edge nodes:

If the distributed PV edge nodes are used as the independent adjustable equipment, the optimization model of distribution network is reformed as follows:

$$Q_{E,i}^\text{Min} + Q_{E,i}^{\text{Real}} \leq Q_{E,i} \leq Q_{E,i}^\text{Max} + Q_{E,i}^{\text{Real}} \quad i = 1...N_E$$

where $Q_{E,i}$ is the reactive power output of edge node $i$. $Q_{E,i}^{\text{Min}}$, $Q_{E,i}^{\text{Real}}$, and $Q_{E,i}^\text{Max}$ are the cooperative variables sent by the edge node.

3.3.3. Optimization process of EC based distribution network. After determining the EC based optimization model of distribution network, the voltage and reactive power optimization problem is described as a quadratic constrained quadratic programming model, so that the optimization solution can be calculated immediately and precisely. The whole process is shown in Figure 3.

**Figure 3.** Reactive power optimization calculation flow of EC based distribution network

4. Simulation and analysis

4.1. Simulation environment

As shown in Figure 4, the 33-node test system of distribution network is used as the initial simulation environment to verify the reactive voltage control method proposed in this paper.
Distributed PV power are connected at nodes 2, 19, 24, 4, 7, 12, 17, 21, 30, 32, etc. The modified system is shown in Figure 5. In the simulation, the active, reactive, and voltage data of the grid-connected point are revised based on the historical data of an actual distributed PV station.

4.2. Effect of EC coordinated control

4.2.1. Uncoordinated state. When the coordinated control of PV is ignored, the optimization result of distribution network is shown in Figure 6, where the node number is X axis and the node voltage is Y axis.
Figures 6 to 8 show that when the coordinated control of PV is ignored, the connection of PV can significantly increase the subsequent node voltages. However, the voltages still descend along the power supply direction, and the PV power generation has little effect on the node voltages.

4.2.2. Coordinated state. In this case, multiple cross-section data are selected for optimization. Similarly, the node voltages after each optimization are compared in Figure 9, where the node number and the node voltage are still X axis and Y axis, respectively.

**Figure 8.** Comparison of nodes voltage (PV Low)

**Figure 9.** Comparison of nodes voltage (PV peak)

**Figure 10.** Comparison of nodes voltage (PV average)

**Figure 11.** Comparison of nodes voltage (PV Low)
From Figure 9 to 11, it is seen that in the coordinated stat, the connection of PV has significantly increase the voltages of access and subsequent nodes. The voltages no longer have a significant descend trend with the power supply. When the PV output is reduced, the higher node voltages have a significant drop, showing that the PV can cut peaks and fill valleys. What’s more, the voltages distribution between nodes are more balanced, and the voltages quality have been significantly improved.

As above discussion, because the immediate adjustment ability of PV is fully utilized in the EC based reactive power optimization system, the voltages quality is much higher and the control is more effective than standard power system.

4.3. Potential of edge coordination
The actual statistics of distributed PV communication in a region of Zhejiang Province is shown in Table 2.

| Number | Grid-connected | Wire channel | High quality signal |
|--------|----------------|--------------|---------------------|
|        | 146            | 11           | 141                 |
| Percent(%) | 100            | 7.5          | 96.6                |

It is seen that, most of distributed PV stations can participate in the reactive power optimization control, except for very few PV stations with low-quality signal. Therefore, the EC-based reactive power optimization system proposed in this paper is expected to be widely used in practice.

5. Conclusion
At first, this paper comprehensively analyses the characteristics and status of coordinated control in distribution network. Secondly, this paper designs the reactive power optimization system of distribution network based on edge calculation to help the PV inverters participate in the coordinate control of voltage regulation and frequency modulation. In the proposed optimization system, the edge nodes are responsible for the collection, analysis, calculation of information, and the communication with master station, so that the coordinated control can be applied to ensure the participation of the PV inverters in reactive voltage control, and thus a novel solution for the distribution network optimization is formed. The effectiveness and correctness of the proposed method have been verified in the simulation of 33-bus system of distribution network.

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