Analysis of Steady-State Operation of Active Distribution Network under Uncertain Conditions

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*Abstract*—Recently, distributed generators (DGs) have been widely integrated into distribution network, so that the distribution network is gradually transforming into an active distribution network (ADN). Due to the influence of meteorological conditions, the output of DGs has high uncertainty. At the same time, considering the increasing variety of loads in ADNs, the uncertainty of load demand of user side is also increasing. In order to fully consider the uncertainty of measurement and quantitatively evaluate the operational status, this paper proposes a steady-state analysis method for ADNs under uncertain conditions. Firstly, this paper proposes a steady-state analysis method including power flow analysis model and evaluation indicators for the operation status from the perspectives of node and network. Secondly, the uncertainty factors are elaborated from three aspects: sources, impact on evaluation index and impact on scheduling. The evaluation indicators considering uncertain conditions, the impact on system security and scheduling of network are further discussed. Finally, through the simulation analysis of the modified IEEE 33-node test system, The effectiveness of the proposed method are verified.

*Index Terms*--Active distribution network, steady-state analysis, distributed generator, uncertain conditions, quantitative evaluation indicators.

# Introduction

Distributed generator (DG) refers to a promising solution to the energy crisis and environmental pollution, which is positive to both economy and reliability [1]. Recently, DGs have been gradually integrated into distribution network. Distribution network has converted to active distribution network (ADN). However, affected by the meteorological conditions, the outputs of DGs have an uncertain characteristic. At the same time, the uncertainty of load demand in ADN has increased considering multiple types of loads and diverse needs of users. The uncertainties of load demand and DG output aggravate the imbalance of supply and demand. Therefore, the uncertainty of net load in ADN increases, which puts forward a higher requirement for the rational dispatch of power flow. On the sight of node, the power cannot be fully balanced [2]. On the lines, the line power is affected by node power imbalance. The fluctuation may lead to loverload or power reversal, which night cause node voltage violation.

In response to the increment of uncertainties in ADN, several research has been carried out. In terms of sources of uncertainty, it mainly focuses on the following three aspects: DG output, load demand, and meter error. Taking into account the differences in industrial manufacturing levels, meter error is inevitable [3]. In which reason load demand and DG output are the main issues we need to focus on. Therefore, one of the main sources of uncertainty in ADN is the inaccurate measurement information, including uncontrollable DG outputs and real-time load demand on the user side. Considering the security risks caused by renewable energy generation forecasting errors, the impact of the uncertainty of DG output is analyzed in [4]. [5] analyzes the impact of extreme weather conditions on users’ load demand. In which reason, the secure operation constraints are emphasized under uncertain conditions. Ref. [6] discussed the voltage deviations and line overloads during peak times brought by the integration of flexible loads. Ref. [7] proposed an optimization method for distribution network considering the security indexes of network. A day-ahead active power scheduling method is proposed in [8], considering the forecast errors caused by the prediction of DG generation level.

However, traditional distribution network has fewer controllable devices and lower adjustment accuracy, so it cannot solve the problem of inaccuracy. With the development of power electronic technology, controllable devices provide opportunity to the reliable and flexible operation of ADN. In recent years, the fully-controlled power electronic devices such as energy storage system and soft open point (SOP) [9] brought opportunity for the flexible dispatch of power flow. For example, SOP can continuously regulate the transmission of active power between feeders while supporting reactive power to the connected nodes. As mentioned in [10], SOP can reduce the line load rate, improve system security by reducing line load rate or reduce voltage deviation. Particularly, when DGs are centralized connected to a feeder, SOP can effectively alleviate power fluctuations by realizing the flow adjustment between feeders. With the improvement of automation level and controllability of the whole system, the ability to adapt to uncertainty is effectively increased. However, under uncertain conditions, in order to ensure the safe and reliable operation of ADN, conservative dispatching strategies of controllable devices are needed.

In order to fully evaluate the operation status of ADN, the widely used methods for quantifying operating status include inter-temporal simulation and optimization method [11]. The current methods have reflected the ability of ADN to cope with the uncertainties of source and load [12], while the parameters in ADN are determined. Furthermore, robust analysis method [13] and scene-generation method [14] are adopted for some uncertain scenarios. Taking into account the non-linear factors in ADN, robust analysis method needs a large aount of computational resources and time consumption. Scene-generation method is affected by the original data set and cannot reflect the extreme operating conditions. Ref. [15] proposed a method for calculation of uncertain power flow, which requires multi-step transformation and significant computing memory. Ref. [16] proposes a flexibility chart to evaluate the operation status of power systems. In Ref. [17], International Energy Agency conducts a cost analysis of resources based on a simplified metric to evaluate the operation of distribtion network. However, these evaluation indexes are prone to be conservative in most cases.

In order to fully consider the uncertainty of the measurement information and quantitatively evaluate the operation status of ADN, a steady-state analysis method of ADN considering uncertain conditions is proposed in this paper. The key contributions of this paper are as follows:

* Facing the operational requirements, a steady-state analysis method for the operation state of ADN is proposed, including power flow model and evaluation indexes of the operation status from the perspectives of nodes and network.
* Considering the uncertain factors in ADN, the source of uncertainty is discussed and the impact on power flow and dispatching of ADN are analyzed. An optimization method for the scheduling of network is elaborated consider the minimum operating margins under the worst scenario.

The rest of the paper is organized as follows: Section II briefly introduces the steady-state model and the evaluation indexes of ADN with controllable devices. Section III discusses the source of uncertainty and the impact on power flow and dispatching of ADN. An optimization method for the scheduling of network is further elaborated consider the minimum operating margins. The simulations and results are shown in Section IV. The conclusion is described in Section V.

# Steady-state analysis of active distribution network

With the widespread access of DG, the power flow of ADN has become more and more complicated. Therefore, it is necessary to construct a calculation model for power flow. The quantitative analysis method for the operation status of the network is also needed. Furthermore, the operation constraints of controllable devices need to be considered.

## Basic assumptions of active distribution network

This paper is oriented to the medium-voltage distribution network, in which reason the following basic assumptions [12] are made:

* ADN is under a stable operating state. There are no oscillations or faults in the system;
* The complex operational status is simplified, three-phase imbalance problem is ignored;
* ADN is supposed to maintain radial operation under steady-state scenarios.

## Steady-state analysis model

In order to ensure the safe and reliable power transmission of ADN, based on DistFlow model, the steady-state analysis model is proposed.

### Power flow constraints of distribution network

In a steady-state ADN, constraint (1) denotes the power flow in the network at time period .

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|  | (1) |
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During time period , and represent the power exchange between grid and node . and represent the active and reactive power of line . is the set of all lines in ADN. and represent the resistance and reactance. represent the current of of line . denotes the voltage amplitude of node .

In a radial network, there is only one path between node and source node. For each node , is defined as a line set of the unique path from node to the source node. It can also be confirmed that there is a power transmission path between the two nodes by the intersection between and . If the intersection of line set and satisfies , it is proved that the nodes and are connected. The connectivity of nodes can be expressed as equation (2). represents the set of lines connecting the paths between node and node .

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| --- | --- |
|  | (2) |

Line power transmission constraints and node voltage constraints are considered, which are limited by the capability of branches and system operational constraints. Secure operation constraint (3) shows that there is no line overloads and node voltage violation. represents the upper limit of line transmission power. and are the lower and upper bounds of node voltage.

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|  | (3) |
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According to the model of linearized DistFlow model [18], the relation constraints between line power, node voltage and power injection are constructed in (1). At the same time, considering the conversion between line power and line current, the nonlinear expression of current in (1) is ignored. Therefore, the relationship of line power, node voltage and net load can be expressed as constraint (4).

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|  | (4) |
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In constraint (4), represents a set of all son nodes including node itself, .

### Operational constraints of controllable devices

In order to optimize the operation status of ADN, various controllable devices are widely integrated. With the development of power electronic technology, the output of controllable devices can be easily adjusted, which can be seen as the state variables dring the optimization process. Take operational constraint of SOP as an example. SOP is a kind of fully-controlled power electronic devices, which can quickly and accurately control its power outputs, thereby regulating the power flow of the entire network [19]. The operational constraints of SOP are shown in constraint (5).

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In constraint (5), and represent the active and reactive power injection by SOP at node during time period , which are used as the control variables. denotes the active power loss of SOP at node during time period . Loss factors are considered in the operational constraints. is defined as the loss coefficient of SOP at node . and represent the upper and lower boundaries of reactive power. denotes the capacity of SOP.

## Evaluation indexes for operating status of ADN

In order to fully grasp the operation status of ADN, it is necessary to evaluate the operation status based on actual operation data. Therefore, in order to quantify the operating status of ADN in a better way, this paper denotes evaluation indexes for the operating status, including evaluation indexes of node and network.

### Evaluation index of node

From the node level, the net load of a node reflects the type of node, including load or source. However, after considering the integration of DG, the type of nodes may vary over time. By connecting controllable device, the net load of the node can be adjusted to increase its regulation capacity. Therefore, based on power node model [20], the power exchange at node can be analyzed. Further considering the operational characteristics of controllable devices, a unified model of power change at node is established. As can be seen in constraint (6) and Fig.1, the power exchange between grid and device is analyzed.

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Constraint (6) represents the power balance at node during time period . If an energy storage system is connected to node, the equivalent storage capacity , otherwise . represents the equivalent state of charge. At the same time, the reactive power cannot be stored. and represent the total power output of DGs. and represent the total value of load demand. and represent the total active and reactive power injection of controllable devices (such as SOP). For example, represents a power supply and denotes an energy absorption. Furthermore, there is an interval of regulating ability of controllable devices connected to node, energy storage devices are limited by their storage capacity , and are defined as the lower and upper boundaries of regulating ability. At the same time, and are defined as the limits of reactive power.



1. Unified model of power exchange at node.

According to the analysis above, from the perspective controllable devices, the regulating ability can be divided into up capacity and down capacity. The power injection into the node is set as the positive direction, in which the up capacity can be quantified as the most power that can be injected, while the down capacity can be calculated by power can be absorbed. In order to maintain schedulable capacity at node, the minimum value of adjustable active power is used to evaluate the power margin of node (PMN), which is a combined index of up capacity and down capacity.

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|  | (7) |
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represents the up capacity of node at time . It can be calculated by adding the output power of energy storage system and controllable resources. Meanwhile is set as the down capacity of node. The index of PMN represents the ability of net load adjustment at each moment , which also represents the distance from the operating point to the scheduling boundary.

### Evaluation index of network

The uncertainty of line transmission power is not conducive to the flexible and reliable operation of ADN, which may cause congestion of line [21]. In the case of line power overload, the line's forward (or reverse) regulation capacity is close to zero. Meanwhile, the volatility of node voltage affects the secure and reliable power supply. The excessive voltage deviation may cause equipment shutdown or insulation breakdown.

The main indicators used in traditional method are load rate (LR) and voltage deviation (VD). Based on the above analysis, in order to quantify the operation status of the whole network, this paper proposes an evaluation index for the operation status of ADN. From the system level, the worst operating part of the network can reflect the operating margin of network (OMN) to an extent. For example, we focus on a line with the highest load rate or a node with the largest voltage deviation. This is similar to the *barrel theory*, take the maximum load rate and the maximum voltage deviation as the combined evaluation index of network, as shown in (8).

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|  | (8) |

In (8), represents the load rate of line . represents the voltage deviation rate of node .

# The source of uncertainty and its impact on active distribution network

## Source of uncertainty

In terms of sources of uncertainty, this paper focuses on the following three aspects: DG output, load demand, meter error.

### DG output

The uncertainty and volatility of DG outputs put forward higher requirements for the operation and scheduling of ADN. There are many types of DGs with different dynamic responses. According to whether they can participate in the operation and scheduling, they can be divided into two types: one is controllable DG, which can be regarded as flexible and controllable resource in the system; the second one is uncontrollable DG, which mainly includes photovoltaics (PV), wind turbines (WT), etc. These DGs mainly use natural resources for power generation, the outputs are affected by the environmental conditions, climate and other factors, such as wind speed, sunshine intensity, temperature, etc. In which reason, uncontrollable DGs are difficult to participate in the flexible dispatch of ADN. Figure 2 is a schematic diagram of PV output (±10%), which shows the fluctuation of the uncontrollable DG. Without considering randomness, the predictive value of DG is used in the process of scheduling of ADN. However, the output of PV may fluctuate between the upper and lower limits, which brings challenges to the existing analytical methods.



1. Schematic diagram of fluctuations of PV output.

### Load demand

The uncertainty of the load is also one of the important factors to be considered to maintain the reliable operation of ADN. In ADN, the uncertainty of load demand has significantly increased since the integration of new types of loads such as electric vehicles. At the same time, affected by the fluctuation of electricity prices and policy orientation, the possibility and enthusiasm of users to actively participate in the optimization of ADN continues to grow. However, the participation of users has randomness and time lag, which makes the uncertainty characteristics of the load demand more complicated. Figure 3 is a schematic diagram of the fluctuation of load demand (±10%).



1. Schematic diagram of fluctuations of load demand.

### Meter error

Considering that each device in ADN needs to upload its data to the control center through the data detection system and the physical information network, it is inevitable that the mass data will be affected by the meter error. For example, when the operating status of the transmission line changes significantly, there is a deviation between the actual value and the calculated value of resistance and reactance of lines. When the accuracy decreases, the uncertainty of ADN increases sharply, which may lead to low data reliability and even cause unobservable problem. Therefore, meter error will become one of the potential weak points of ADN.

## The impact of uncertainty on evaluation indexes

Considering the uncertainty in ADN, the actual load demand and the output of DG deviate from the predicted value, which can be regarded as system fluctuating near the predicted operating point. Under the constraint of uncertain demand, the operation strategy of controllable resources is relatively conservative compared with the value under deterministic conditions. Focusing on the active power of controllable equipment with rapid response, the operating strategy of controllable devices in ADN under uncertain conditions can be expressed as (9) and Fig.4.

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|  | (9) |
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In constraint (9), is defined as the set of available operation strategy of controllable device integrated into node at time . The actual value fluctuates around predicted value, and represent the predicted load demand and DG output, - represent the fluctuation coefficients, which are set according to predicted deviation value.



1. Unified model of power exchange considering the uncertain factors.

The index of PMN is used in scenarios where there is no lack of controllablity in the system, which reflects the adequacy of system regulating ability. In which reason equation (8) can be rewritten as (10). After considering the uncertain parameters in ADN, the possible indicator of PMN will increase, since non negative numbers are added in the equations.

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|  | (10) |
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## The impact of uncertainty on security and scheduling of ADN

Further analyze the power transmission through network, considering that the randomness of nodes increases, the power flow in ADN becomes more complex. According to equation (4), the net load and on the node side are important factors affecting the operating status of the system, so the calculation of net load considering the uncertain factors can be represented as:

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In (11), the power factors of load and DG are assumed to remain constant, so the randomness of reactive power and active power remain consistent. Therefore, in order to ensure the stability of net load, more factors are further considered when the operating strategy (,) of controllable devices are made by dispatchers. Further consider the system operation and index OMN in equation (8), to maintain the index OMN under deterministic conditions, conservative dispatching strategies of controllable devices are needed. At the same time, further considering the fitting method of operating curve, the accuracy of the weather forecast can be improved to deal with the uncertain conditions in ADN. At the same time, further considering the fitting method of operating curve, the accuracy of the weather forecast can be improved to deal with the uncertain conditions in ADN. Data-driven method can be used to effectively generate the data set to reflect the local weather, in which the fluctuation coefficients can be reduced.

Based on the above analysis, in the scheduling of controllable devices in ADN considering randomness factors, the first step is to analyze the initial operating status of ADN and calculate the prime number of OMN index based on the predicted value of DG and load. Determine whether the indicator OMN can meet the minimum margin required by the system. If , then the objective function is set to reduce system operating losses, as can be seen in (12).

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| --- | --- |
|  | (12) |
|  |

is the objective function, is the objective function for reducing system losses. is the total number of time periods for analysis, is the total active load on node. is the analysis step.

Else if , at this point, the system is not sufficient to alleviate the challenges brought by randomness. In which reason the large-M method can be used to construct an objective function for ADN, as can be seen in (13). If OMN is less than the minimum margin required for scheduling, the operating strategies of controllable devices are calculated considering the worst scenario to maintain the minimum margin.

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|  | (13) |
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M is a large constant, usually taken as 100. is the objective function for opearting margin. is the total number of all load nodes in the distribution network.



1. Flow chart of analyzing system operating status under uncertain condistion.

# Case study

To verify the effectiveness of the proposed method, a modified IEEE 33-node test system [22] is adopted. Figure 6 shows the structure of the distribution network. To ensure the security of distribution network, the limit of the transmission capacity of lines is set to 5 MVA and the upper and lower limits of node voltage are set as 1.1 - 0.9 (p.u.). The PV access points are nodes 12, 14, 16 and 18, with the capacity of 400.0 kVA and inverter power factor set to 0.9. Considering the time sequence analysis of 24 hours, the simulation step is set as 1 hour. The location of SOP is set at node 18 and 33, the capacities of SOPs are set as 1 MVA and loss coefficient is set to 0.02. The proposed method is implemented in the YALMIP [23] optimization toolbox using MATLAB R2014a and solved by CPLEX 12.4.



1. Modified IEEE 33-node system

## The impact of uncertainty on evaluation index

To quantitative evaluate the influence of uncertainty in ADN, the evaluation index of PMN and OMN are used. In this section, the fluctuation of operational curves are adopted to describe the uncertainty of DG outputs and load demands, which can be seen in Fig.2 and Fig.3. The threshold of fluctuation range is set as ± 10%. Three scenarios are adopted. The minimum margin required by the system is set to 0, which means there is no line overload or voltage violation in ADN. The PMNs for controllable devices access points are calculated.

Scenario I: The initial operation status of ADN is obtained.

Scenario II: The uncertainty of DG is considered with the range of ± 10%.

Scenario III: The uncertainty of load is further considered, with the load fluctuation range of ± 10%.

The simulation results are shown in Table I and Table II. Table I shows the operation status of nodes with regulating ability. Firstly, the opration status is analyzed from the node level. Considering that the location of SOP is node 18 and 33, under deterministic conditions, the operating margin at node 18 or 33 is the maximum active power that SOP can output, based on the goal of reducing system losses in Scenario I. The power transmission of SOP in Scenario I is shown in Fig.7 and Fig. 8. Compared with Scenario I and II, the uncertainty of DG at node 18 improve the down capacity of node, but the up capacity is not changed since the occurance time is at time 20:00 when the PV output is zero. The index at node 33 is not changed since there is no DG integrated. Compared with the results in Scenario II and III, randomness will improve the PMN index to some extent from the sight of a single node.

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| **Scenario** | **Node 18** | **Node33** |
| I | (894.6, 404.1) | (282.9, 651.8) |
| II | (894.6, 422.1) | (282.9, 651.8) |
| III | (896.9, 425.3) | (285.9, 654.6) |

1. Operation Status of Source Nodes Considering the Uncertain Factors



1. Active power of SOP in Scenario I



1. Reactive power of SOP in Scenario I

However, when analyzing from the system level, the simulation results are shown in Table II. The LR indexes and VD indexes are proposed. As the random factors in the distribution network continue to increase, the index of OMN decreases. The main reason for this result is that the uncertainty of node net load will lead to increment in the fluctuation of line load and node voltage. Therefore, using OMN indicators for evaluating system operation status is more comprehensive.

The fluctuation of OMN in Scenario III is shown in Fig.9. The red curve represents the node voltage deviation value of OMN indicator, the blue curve represents the line load rate value. To represent the uncertainty of OMN, Fig.10 and Fig.11 are adopted. The gray area represents the fluctuation area of the indicator considering the randomness of DG and load, while the red curve shows the optimal case and the blue curve shows the worst case. The time when the OMN index is low is mainly concentrated on 09:00 - 10:00 and 16:00 - 18:00, which is the time period when the PV output is high.

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| --- | --- | --- | --- |
| **Scenario** | **LR(p.u.)** | **VD(p.u.)** | **OMN(p.u.)** |
| I | 0.2070 | 0.2054 | (0.7930, 0.7946) |
| II | 0.2101 | 0.2094 | (0.7899, 0.7906) |
| III | 0.2362 | 0.2452 | (0.7638, 0.7548) |

1. Operation Status of Network Considering the Uncertain Factors



1. Temporal characteristics of OMN in Scenario III.



1. The uncertainty of OMN on lines.



1. The uncertainty of OMN on nodes.

## The impact of the fluctuation amplitude of uncertainty on evaluation index

Furthermore, considering the scenario of inaccurate measurement of DG and load, the fluctuation threshold of DG output and load demand are all set as ± 20%, ± 30%, ± 40% and ± 50%, as mentioned from Scenario IV to VII. Compared with Scenario I and III, the operating status of ADN under different fluctuation amplitude are further evaluated.

Scenario IV: The uncertainty factors are set as ± 20%.

Scenario V: The uncertainty factors are set as ± 30%.

Scenario VI: The uncertainty factors are set as ± 40%.

Scenario VII: The uncertainty factors are set as ± 50%.

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| --- | --- | --- | --- |
| **Scenario** | **LR(p.u.)** | **VD(p.u.)** | **OMN(p.u.)** |
| I | 0.2070 | 0.2054 | (0.7930, 0.7946) |
| III | 0.2362 | 0.2452 | (0.7638, 0.7548) |
| IV | 0.2671 | 0.3000 | (0.7329, 0.7000) |
| V | 0.2965 | 0.3684 | (0.7035, 0.6316) |
| VI | 0.3196 | 0.4423 | (0.6804, 0.5577) |
| VII | 0.3459 | 0.5388 | (0.6541, 0.4712) |

1. Operation Status of Network under Different Fluctuation Amplitude

The simulation results of different fluctuation range are shown in Table III. After considering the fluctuation of load demand and DG output, the indexes of LR and VD have a significant change. The possible LR and VD indicators continue to rise, in which reason the OMN index is reduced with the increment of fluctuation amplitude. The relationship between OMN indicators and the fluctuation level of uncertainty can be seen in Fig.12. It can be seen that compared to the line indicator, the node voltage indicator is more sensitive to uncertainty factors. The main reason is that uncertainty not only affects the net load of nodes, but also affects the power of lines, further increasing the fluctuation of node voltages.



1. The relationship of OMN and uncertainty.

## Scheduling of controllable devices under uncertain conditions

In this section, the operating strategies of SOP are calculated to maintain the minimum margin. The minimum margin required by the system is set to 0.5, which means the load rate and voltage deviation are restricted to within 0.5. The optimization model is applied under Scenario VII, where the uncertainty factors are set as ± 50%. The load demand and DG output under worst case are shown in Fig.13. Considering the uncertain condistion that has the greatest impact on indicators, after the optimization of ADN, the active and reactive power of SOP are shown in Fig.14 and Fig.15. Compared with the power output of SOP under Scenario I, the operating strategy become more conservative on active power. At the same time, the output of reactive power is higher, specifically reflected in the optimization of terminal node voltage.



1. Operating curve of active distribution network under the worst case.



1. Active power of SOP in Scenario VII with minimum margin.



1. Reactive power of SOP in Scenario VII with minimum margin.

# Conclusion

Distributed generators have been widely integrated into distribution network, due to the influence of meteorological conditions, the output of DGs has high uncertainty. At the same time, considering the increasing variety of loads in ADNs, the uncertainty of load demand of user side is also increasing. In order to fully consider the uncertainty of measurement and quantitatively evaluate the operational status, a steady-state analysis method for ADNs under uncertain conditions is proposed. Firstly, this paper proposes a steady-state analysis method including power flow analysis model. The evaluation indicators of power margin of node (PMN) and operating margin of network (OMN) are elaborated from the perspectives of node and network. Secondly, the uncertainty factors are elaborated from three aspects: sources, impact on evaluation index and impact on scheduling. The evaluation indicators considering uncertain conditions, the impact on system security and the scheduling of controllable devices are further discussed. Finally, through the simulation analysis of the modified IEEE 33-node test system, The effectiveness of the proposed method are verified. Results show that the proposed evaluation indicators can evaluate the operation of the system from multiple levels. By accessing controllable devices such as SOP, the impact of uncertain factors in ADN can be effectively alleviated.

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