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QUANTIFICATION ANALYSIS OF FEEDER OPERATIONAL FLEXIBILITY FOR ACTIVE DISTRIBUTION NETWORKS

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ABSTRACT

With the high penetration of distributed generators (DGs), it puts higher requirements on the operational flexibility of active distribution networks (ADNs). Operational flexibilities are from controllable resources (CRs) within the feeders. However, due to the secure operational constraints of distribution network, the flexibilities of CRs cannot be fully translated into feeder operational flexibilities. In this paper, to quantify the feeder operational flexibility for flexible, efficient and secure operation of ADNs, a quantification analysis method is proposed. The definition and mathematical expression of feeder operational flexibility are proposed firstly. By constructing a multi-dimensional state space, state equations of operational constraints are presented. Then an analytical framework for quantifying the feeder operational flexibility in ADNs is proposed. Finally, based on Monte Carlo simulation, case studies are performed on the modified IEEE 33-node system.

Keywords: feeder operational flexibility; active distribution network; controllable resources; Monte Carlo simulation

NONMENCLATURE

Abbreviations

DG	Distributed Generator
ADN	Active Distribution Network
CR	Controllable Resource
ESS	Energy Storage System
SVC	Static Var Compensator

Symbols

$p_i^{\mathrm{net}}/q_i^{\mathrm{net}}$	Net active/reactive load at node i
$\zeta_i^{\mathrm{P}}/\zeta_i^{\mathrm{Q}}$	Active/reactive power output of uncontrollable device at node i
$\omega_i^{\mathrm{CR,P}}/\omega_i^{\mathrm{CR,Q}}$	Active/reactive power outputs of CRs at node i
$\underline{\omega}_i^{\mathrm{CR,P}}/\overline{\omega}_i^{\mathrm{CR,P}}$	Lower and upper bound of active power outputs of CRs at node i
$\underline{\omega}_i^{\mathrm{CR,Q}}/\overline{\omega}_i^{\mathrm{CR,Q}}$	Lower and upper bound of reactive power outputs of CRs at node i
P_{ij}/Q_{ij}	Active/reactive power on line ij
v_0	Squared voltage magnitude of source node
v_i	Squared voltage magnitude of node i
r_{hk}/x_{hk}	Resistance/reactance of line hk
$\overline{S}_{ij}$	Upper bound of transmission capacity on line ij
$\underline{v}/\overline{v}$	Lower and upper bound of voltage

1. INTRODUCTION

With the high penetration of distributed generators (DGs) in active distribution networks (ADNs) [1], the fluctuation of DG aggravates the imbalance of power supply and demand of ADNs. It puts forward higher requirements on the operational flexibility of ADNs [2].

Operational flexibility is usually from the controllable resources (CRs) at nodes. CRs such as electric vehicles, energy storage system (ESS) and static var compensator (SVC) can effectively improve node flexibility by adjusting operation strategies to meet operational requirements [3]. As nodes are connected and interactive through feeders, node flexibility constitutes feeder operational flexibility. However, due to the secure operational constraints of distribution network, the flexibilities of

CRs cannot be fully translated into feeder operational flexibilities.

Previous studies have investigated the quantification method of operational flexibility. In [4], a quantified analysis method of flexibility insufficiency is proposed. However, when the supply and demand is balanced in ADNs, the existing methods will no longer apply. There is still a lack of quantification analysis method of feeder operational flexibility for flexible, efficient and secure operation.

In this paper, to quantify feeder operational flexibility for flexible, efficient and secure operation of ADNs, a quantification analysis method is proposed. The definition and mathematical expression of feeder operational flexibility are proposed firstly. By constructing a multi-dimensional state space, state equations of operational constraints are presented. Then an analytical framework for quantifying feeder operational flexibility in ADNs is proposed. Finally, based on Monte Carlo simulation, case studies are performed on the modified IEEE 33-node system.

2. DEFINITION AND MATHEMATICAL EXPRESSION OF FEEDER OPERATIONAL FLEXIBILITY

2.1 Definition of feeder operational flexibility

In this paper, feeder operational flexibility is defined as the regulating capacity that feeder can provide under secure operation conditions, which means all the operation constraints of power flow, node voltage and branch current are satisfied simultaneously.

2.2 Basic assumptions

In ADNs, if the fluctuation around the current operating state is small enough, we consider the following supposed conditions:

1) The superposition theorem is satisfied by using linearized DistFlow equations [5].

2) Three-phase imbalance in ADNs is ignored.

3) There is no loop in the feeder.

2.3 Mathematical model of feeder operational flexibility

2.3.1 State variables and state space

Load demands and outputs of uncontrollable devices in ADNs are determined. On the contrary, the operation strategies of CRs within the feeder can be changed in order to meet operational requirements, which can be set as the state variables. All the state variables consist of the multi-dimensional state space. The dimension of state space is equal to the number of operation strategies.

2.3.2 State equations

Considering the outputs of uncontrollable devices and operation strategies of CRs, a general description of node flexibility is established based on the power node model [2].

1) Equation of active power at node

$$
\begin{aligned}
& p_i^{\text{net}} = \zeta_i^{\text{P}} + \omega_i^{\text{CR,P}} \\
\text{s.t.}\quad & \underline{\omega}_i^{\text{CR,P}} \le \omega_i^{\text{CR,P}} \le \overline{\omega}_i^{\text{CR,P}}
\end{aligned} \tag{1}
$$

2) Equation of reactive power at node

$$
\begin{aligned}
& q_i^{\text{net}} = \zeta_i^{\text{Q}} + \omega_i^{\text{CR,Q}} \\
\text{s.t.}\quad & \underline{\omega}_i^{\text{CR,Q}} \le \omega_i^{\text{CR,Q}} \le \overline{\omega}_i^{\text{CR,Q}}
\end{aligned} \tag{2}
$$

Based on equation (1) and (2), state variables of node i can be expressed as $\{\omega_i^{\text{CR,P}}, \omega_i^{\text{CR,Q}}\}$.

By linearizing the DistFlow equations [5], line power transmission and node voltage can be expressed as equation (3) and equation (4).

3) Line power transmission

$$
\begin{aligned}
P_{ij} &= \textstyle\sum_{k\epsilon\beta(j)}(\zeta_k^{\text{P}} + \omega_k^{\text{CR,P}}) \\
Q_{ij} &= \textstyle\sum_{k\epsilon\beta(j)}(\zeta_k^{\text{Q}} + \omega_k^{\text{CR,Q}})
\end{aligned} \tag{3}
$$

$\beta(j)$ represents a set of all son nodes including node j itself.

4) Node voltage

$$
\begin{aligned}
v_0 - v_i = & \; 2\textstyle\sum_{j\in\mathcal{N}}\left(\zeta_k^{\text{P}} + \omega_k^{\text{CR,P}}\right)\left[\sum_{(h,k)\epsilon\mathcal{L}_i\cap\mathcal{L}_j} r_{hk}\right] \\
& +2\textstyle\sum_{j\in\mathcal{N}}\left(\zeta_k^{\text{Q}} + \omega_k^{\text{CR,Q}}\right)\left[\sum_{(h,k)\epsilon\mathcal{L}_i\cap\mathcal{L}_j} x_{hk}\right]
\end{aligned} \tag{4}
$$

$\mathcal{N}$ represents the total number of nodes within the feeder. $\mathcal{L}_i$ is defined as a line set of the unique path from node i to the source node. To simplify equation (4), the overall line resistance R_{ij} and line reactance X_{ij} are introduced:

$$
\begin{aligned}
R_{ij} &\coloneqq \textstyle\sum_{(h,k)\epsilon\mathcal{L}_i\cap\mathcal{L}_j} r_{hk} \\
X_{ij} &\coloneqq \textstyle\sum_{(h,k)\epsilon\mathcal{L}_i\cap\mathcal{L}_j} x_{hk}
\end{aligned} \tag{5}
$$

Equation (4) can be simplified as:

$$
\begin{aligned}
v_0 - v_i = & \; 2\textstyle\sum_{j\in\mathcal{N}}\left(\zeta_k^{\text{P}} + \omega_k^{\text{CR,P}}\right)R_{ij} \\
& +2\textstyle\sum_{j\in\mathcal{N}}\left(\zeta_k^{\text{Q}} + \omega_k^{\text{CR,Q}}\right)X_{ij}
\end{aligned} \tag{6}
$$

By establishing the relation constraints of secure operation constraints and the operation strategies of CRs, the available operation strategies can be obtained. The initial operation points before accessing CRs are set as P_{ij}^0, Q_{ij}^0 and v_i^0.

5) Line power transmission constraint

$$
\begin{aligned}
& \left(P_{ij}^0 - \textstyle\sum_{k\epsilon\beta(j)}\omega_k^{\text{CR,P}}\right)^2 \\
& +(Q_{ij}^0 - \textstyle\sum_{k\epsilon\beta(j)}\omega_k^{\text{CR,Q}})^2 \le \overline{S}_{ij}^2
\end{aligned} \tag{7}
$$

6) Node voltage constraint

$$\begin{aligned}\underline{v}^2 \le v_i^0 + 2\textstyle\sum_{j\in\mathcal{N}}\left(\omega_i^{\mathrm{CR,P}}\right)R_{ij} \\ +2\textstyle\sum_{j\in\mathcal{N}}\left(\omega_i^{\mathrm{CR,Q}}\right)X_{ij} \le \overline{v}^2\end{aligned} \quad (8)$$

Considering the above two secure operation constraints, feeder operational flexibility can be obtained.

3. QUANTIFIED ANALYSIS OF FEEDER OPERATIONAL FLEXIBILITY

3.1 Quantitative analysis method

In this paper, a 2D plane is used to quantify feeder operational flexibility, which is called the flexible region. The X axis of flexible region stands for the active power while Y axis stands for reactive power. The feeder operational flexibility can be quantified in the 2D plane by linear mapping:

$$\begin{aligned}\textstyle\sum P^{\mathrm{flex}} = \sum_{i\in\mathcal{N}} \omega_i^{\mathrm{CR,P}} \\ \textstyle\sum Q^{\mathrm{flex}} = \sum_{i\in\mathcal{N}} \omega_i^{\mathrm{CR,Q}}\end{aligned} \quad (9)$$

In the flexible region, the coordinate ($\sum P^{flex}$,$\sum Q^{flex}$) of each point stands for the sum of active and reactive power that CRs within the feeder can provide. The area of nodes in the flexible region represents the total amount of feeder operational flexibility. Furthermore, the variety of area in the flexible region represents the change of flexibility.

3.2 Quantitative analysis process

Based on the analysis above, the process of quantifying feeder operational flexibility in ADNs can be expressed as follows, also is shown in Fig. 1.

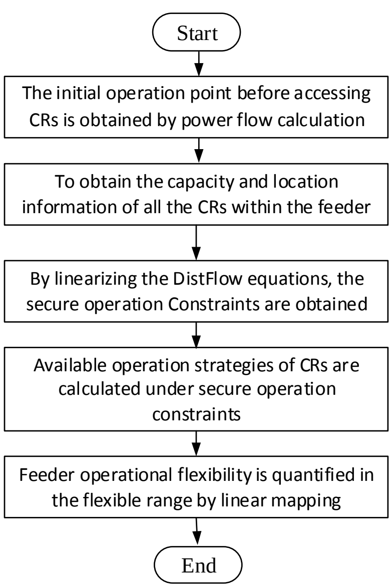

Fig 1 Flow chart of quantification analysis of feeder operational flexibility in ADNs

1) The initial operation point before accessing CRs is obtained by power flow calculation.

2) To obtain the capacity and location information of all the CRs within the feeder.

3) By linearizing the DistFlow equations, the secure operation constraints are obtained.

4) Available operation strategies of CRs are calculated under secure operation constraints.

5) Feeder operational flexibility is quantified in the flexible region by linear mapping.

4. CASE STUDY

The modified IEEE 33-node distribution system is shown in Fig. 2, one of the feeders (6-18) is chosen to verify the proposed method. Four DGs are integrated into the ADNs, as shown in Tab. 1. CRs within the feeder include ESS with a capacity of 3 MVA at node 15 and SVC with a capacity of 1 Mvar at node 16. The feeder operational flexibility under different constraints are quantified by Monte Carlo simulation, the sampling number is set as 10^6.

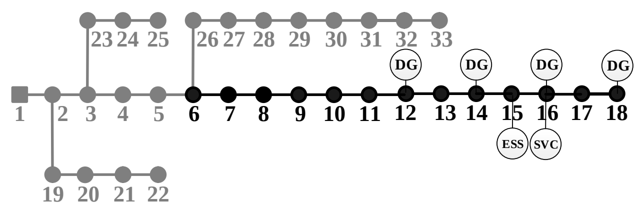

Fig 2 Structure of the modified single feeder in ADNs

Tab 1 Location and capacity of DGs

Locations of DGs	12	14	16	18
Capacity (MW)	1	1	1	1

Feeder operational flexibility is quantified in a certain time, when the load demand is 0.55 p.u. while the DG output is 0.64 p.u.. The capacity of line power transmission is set as 2.5 MVA. The lower and upper bounds of system voltage are set from 0.95 p.u. to 1.05 p.u. Three scenarios are set to quantify the feeder operational flexibility under different constraints.

Scenario I: Without secure operation constraints, the initial feeder operational flexibility is obtained.

Scenario II: Node voltage constraint is considered.

Scenario III: Line power transmission constraint is further considered.

1) Scenario I

The flexibilities of CRs can be fully translated into feeder operational flexibility without considering secure operation constraints, as is shown in Fig. 3.

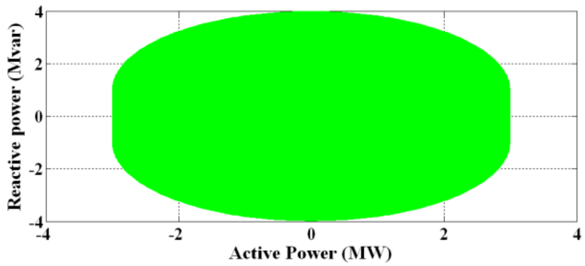

Fig 3 Operational flexibility region of CRs

2) Scenario II

The feeder operational flexibility under node voltage constraints is shown in Fig. 4.

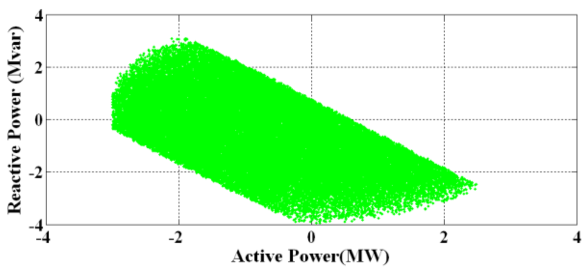

Fig 4 Operational flexibility region under node voltage constraints

3) Scenario III

Under the line power transmission constraints, the operation strategies of CRs are further limited, the flexibility under secure operation constraints is shown in Fig. 5.

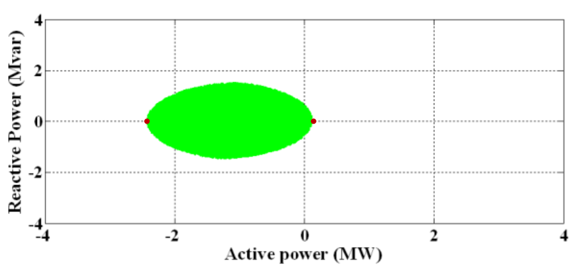

Fig 5 Operational flexibility region under secure operation constraints

The operational flexibility in each scenario is shown in Tab. 3. Without line overload and voltage violation, the feeder operational flexibility is 5.6319 MVA.

Tab 3 Feeder operational flexibility

	Scenario I	Scenario II	Scenario III
Feeder operational flexibility (MVA)	40.2743	20.5600	5.6319

To verify the accuracy of the proposed method, IPOPT is used to solve the maximum and minimum active power outputs of CRs, which can be seen as the left and right boundaries of operational flexibility region. The red points in Fig. 5 shows the specific boundary points. As can be seen from results in Tab. 3, the accuracy of proposed method is acceptable.

Tab 3 Comparison of the proposed method and IPOPT

	Proposed method	IPOPT
Maximum active power output of CRs (MW)	0.1094	0.1088
Minimum active power output of CRs (MW)	-2.4184	-2.4202

5. CONCLUSION

The fluctuation of DGs puts a higher requirement for the operational flexibility in ADNs. Operation flexibilities are from CRs within the feeders. Due to secure operational constraints, the flexibilities of CRs cannot be fully translated into feeder flexibility. In this paper, a quantification method of feeder operational flexibility for flexible, efficient and secure operation in ADNs is proposed. Mathematical expression of operational constraints in ADNs are presented in state space. Based on Monte Carlo simulation, case studies are performed on the modified IEEE 33-node system. By comparison of IPOPT, the accuracy of the proposed method is verified. In the operational scheduling of ADNs, the scheduling scheme of CRs can be obtained by the proposed method.

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