Operational Flexibility Evaluation of Distribution System with High-penetration Distributed Generation

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Abstract: Considering the uncertainty caused by the integration of high-permeability distributed generation into the distribution system, it is necessary to evaluate and enhance the operational flexibility of the distribution system. Firstly, the connotation and characteristics of operational flexibility are introduced, and the relevant factors affecting the operational flexibility are analyzed. Considering the probability of the load scenario, the quantitative operational flexibility evaluation index is proposed. Finally, using IEEE 33 node distribution system to prove operational flexibility evaluation index is reasonable and the role of energy storage devices in improving the operational flexibility.

1. Introduction

With the development of renewable energy, high-permeability Distributed Generation (DG) put into power distribution systems has become an inevitable trend [1]. The ability of distribution system to deal with uncertainties caused by fluctuating output of DG has become the focus of researchers' attention. Operational flexibility is an important indicator to measure the ability of the system to cope with uncertainties [2]. Only when the distribution system has sufficient operational flexibility can it accept a higher proportion of DG. Therefore, it is important to study and evaluate the operational flexibility of distribution systems with high-penetration DG.

Experts and scholars have done a lot of research on the operational flexibility evaluation. Aiming at the power uncertainty caused by renewable energy generation, a mathematical model for measuring system flexibility and an operational flexibility evaluation index are proposed in Literature [3]. Considering the prediction error of renewable energy output, literature [4] found the probability distribution of the available flexibility resources of the system at a given time scale, and proposed practical indicators. From the point of view of supply and demand balance, literature [5] considering the change of climbing capacity and load of generating units, proposed a quantitative index for flexibility evaluation. Literature [6] summarized the evaluation methods of power system flexibility at home and abroad. In summary, most of the above documents are used to evaluate the power system operational flexibility. The research on operational flexibility of distribution system is still in its infancy, and there is still a lack of specific methods for evaluating operational flexibility of distribution system.

A method for evaluating the operational flexibility of distribution systems is proposed in this paper. Firstly, the connotation and characteristics of the operational flexibility of the distribution system are...
given, and the relevant factors affecting the operational flexibility are analyzed. Then, considering the network voltage constraint, based on the improved fuzzy C-means clustering algorithm, the load scenario is divided. Considering the probability of the load scenario, the quantitative operational flexibility evaluation index is proposed. This evaluation index can be used to evaluate the distribution system in terms of spatial and temporal aspects. Finally, based on the improved IEEE33 node example, the correctness of the index is verified, and the energy storage device enhances the operational flexibility of the power distribution system is verified.

2. Operational flexibility of the distribution system

2.1. The connotation of operational flexibility

The operational flexibility of the distribution system refers to the ability of the dispatchable resources to quickly adapt to the operating environment and maintain the safe and stable operation when the system faces various uncertain disturbances (for example: DG’s volatility output, load fluctuations, etc.) at different time scales. Operational flexibility is an inherent feature of distribution systems, allowing the operation to deviate from the preset operating point or be in a critical steady state for a certain degree or time, with the increase of deviation degree, the operational flexibility decreases gradually.

2.2. Influencing factors of operational flexibility

2.2.1. DG

Affected by the natural environment, DG output has the characteristics of uncertainty and variability. At a certain time scale $\Delta T$, the DG output sequence at node $i$ is $P_{Gi} = \{P_{Di}^1, P_{Di}^2, ... P_{Di}^k, ... P_{Di}^T\}$. At time $k$, the output fluctuation value of DG can be expressed as $\Delta P_{DGik} = \Delta P_{DGik+1} - \Delta P_{DGik}$. There are two directions for DG output to increase and decrease, that is, the positive and negative values of $\Delta P_{DGik}$ correspond to the upward and downward operational flexibility of distribution system respectively.

Through calculation, the DG output fluctuation sequence $\Delta P_{Gi}$ at each time can be obtained:

$$\Delta P_{Gi} = \{[P_{DGi}^2 - P_{DGi}^1], [P_{DGi}^3 - P_{DGi}^2], ... [P_{DGi}^{k+1} - P_{DGi}^k], ... \}$$

(1)

The magnitude of $\Delta P_{Gi}$ can reflect the fluctuation degree of DG output and the probability of insufficient operational flexibility of distribution system. The maximum DG output fluctuation that the distribution system can withstand is $\Delta P_{max}$. By comparing the DG output fluctuation sequence $\Delta P_{Gi}$ with $\Delta P_{max}$, the time of insufficient operational flexibility can be screened out and its severity can be quantified.

2.2.2. Load Side

Using typical load scenarios to characterize load characteristics is of great significance for evaluating the operational flexibility of distribution system. This paper refers to the improved fuzzy C-means clustering algorithm. Within $p$ days, the load data of $q$ equal time intervals are collected every day for cluster analysis, the load data sample can be divided into $h$ scenes according to the optimal cluster number $h$. The cluster center of $h$ scenes is expressed as:

$$v_b^{(s)} = (v_{b1}^{(s)}, v_{b2}^{(s)}, ..., v_{bs}^{(s)})^T$$

(2)

Where: $b = 1, 2, ..., h, s (s \geq 1, s \in N)$ - the iteration step, and $s = 1$ at the beginning.

It is assumed that the number of iteration steps is $s = S$, the clustering is completed, and $h$ typical load scenarios are obtained. If the number of original load samples included in the typical load scenario $h$ is $p_h$, then the proportion of the typical load scenario $h$ is $H_h = p_h / p$.

The load fluctuation index of the scene in the sampling period can be used to reflect the fluctuation characteristics of the typical scene of the load. The index reflects the fluctuation degree of typical load scenarios, The index reflects the fluctuation degree of typical load scenarios. The load fluctuation index $E_{flu}$ is:
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Where: $n=1,2,…,q-1$. T - sampling period. $P_c$ - the total rated load of the system.

2.2.3. Energy storage device

The energy storage device is an important part of the power distribution system. Energy storage in a discharged state can provide upward flexibility by increasing discharge power, or provide downward flexibility by reducing discharge or even reverse charging. Energy storage in a charged state provides upward flexibility by reducing charging or even discharging, or providing downward flexibility by increasing charging power.

2.2.4. Time scale

The response characteristics of various schedulable resources of the distribution system are closely related to the time. Therefore, the choice of time scale has a significant impact on the evaluation of the operational flexibility. The value range of time scale $\Delta t$ is as follows: $\Delta t\{1\text{min},5\text{min},30\text{min},1\text{h}\}$.

3. Operational flexibility evaluation index of distribution system

When high-penetration DG put into the power distribution system, the phenomenon of power imbalance increases, which causes the node voltage to change, which in turn causes serious consequences such as voltage overshoot. The ability of nodes to tolerate voltage fluctuation reflects the operational flexibility of distribution system. This paper evaluated the operational flexibility of distribution system from the spatial point of view by using the node flexibility margin index (NFM), and evaluates the operational flexibility of distribution system from the time point of view by using the system flexibility margin index (SFM).

3.1. Node flexibility margin index

NFM is divided into two directions of increase or decrease, which are respectively recorded as $\Delta U_i^+$ and $\Delta U_i^-$. In the case of considering the load scenario and the system safety operation constraints, the margin of the voltage fluctuation that the node can withstand is as follows:

$$E_{\text{lim}}^n = \frac{1}{q-1} \sum_{n=1}^{q-1} \left| y(n_{\text{lim}}) - y(n) \right| \times 100\%$$

(3)

Where: $n=1,2,…,q-1$. $T$ - sampling period. $P_c$ - the total rated load of the system.

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- $n=1,2,…,q-1$. $T$ - sampling period. $P_c$ - the total rated load of the system.

$\Delta U_i^+$ - the upward margin. $\Delta U_i^-$ - the downward margin.

NFM refers to the probability that the node voltage fluctuation does not exceed the voltage fluctuation margin within a certain operation period $T$, which can reflect the operational flexibility of each node. The calculation method is as follows:

$$I_{\text{NFM},i} = \text{Pr} \left\{ \sum_{j=1}^{t} (\Delta U_{R_i,j}^+ \leq F_{\text{BFC},i}^+) + \sum_{j=1}^{t} (\Delta U_{R_i,j}^- \geq F_{\text{BFC},i}^-) \right\}$$

(5)

Where:

- $I_{\text{NFM},i}$ - the flexibility index of node $i$. $\Delta U_{R_i,j}^+$ - the upward fluctuation of voltage at node $i$ at time $t$. $\Delta U_{R_i,j}^-$ - the downward fluctuation of voltage at node $i$ at time $t$.

3.2. System flexibility margin index

SFM can reflect the overall operational flexibility of the power distribution system at various times, and can be expressed by the probability that the voltage fluctuation of each node at $t$ time does not exceed the voltage fluctuation margin range.

$$I_{\text{SFM},t} = \text{Pr} \left\{ \sum_{i=1}^{N} (\Delta U_{R_i,t}^+ \leq F_{\text{BFC},t}^+) + \sum_{i=1}^{N} (\Delta U_{R_i,t}^- \geq F_{\text{BFC},t}^-) \right\}$$

(6)

Where:

- $I_{\text{SFM},t}$ - the system flexibility index at $t$ time. $N$ - the number of nodes in the distribution
system.

3.3. Constraints

\[
\begin{align*}
P_{\text{ess,min}} & \leq P_{\text{ess}} \leq P_{\text{ess,max}} \\
E_{\text{ess,min}} & \leq E_{\text{ess}} \leq E_{\text{ess,max}} \\
U_{i,\text{min}} & \leq U_i \leq U_{i,\text{max}}
\end{align*}
\]  \tag{7}

Where: \(U_{\text{min}}\) - the lower limit of voltage at node \(i\). \(U_{\text{max}}\) - the upper limit of voltage at node \(i\). \(P_{\text{ess,min}}\) - the minimum values of rated power of energy storage. \(P_{\text{ess,max}}\) - the maximum values of rated power of energy storage. \(E_{\text{ess,min}}\) - the minimum values of rated capacity of energy storage. \(E_{\text{ess,max}}\) - the maximum values of rated capacity of energy storage.

4. Case analysis

In this paper, the improved IEEE33 distribution system is used to evaluate the operational flexibility of the distribution system with high-penetration DG. DG are exemplified by photovoltaic (PV) and wind turbine (WT). The PV stations are located at node 5 and node 20. The WT are located at node 2 and node 33. \(U_B=12.66\text{kV}\), \(S_B=100\text{MW}\) The maximum limitation of fluctuation of wind and PV are 0.2MW. The test results of PV and WT are shown in Figure 1. The proportion of typical load scenarios and \(E_{\text{ess}}^5\) are shown in Table 1.

As shown in Figure 1, the PV output fluctuation exceeds the allowable fluctuation range at time 7, 8, 9, 16, 17, 18, 19. WT output fluctuations exceed the allowable fluctuation range at time 5, 6, 8, 9, 19, 21. And wind or light is discarded during the above periods.

![Figure 1: The test result of Photovoltaic and wind power](image)

**Table 1 Typical load scenario parameters**

| Typical load scenario | 1    | 2    | 3    | 4    |
|-----------------------|------|------|------|------|
| Proportion            | 0.312| 0.292| 0.202| 0.194|
| \(E_{\text{ess}}^5\)  | 2.7% | 1.9% | 2.8% | 2.1% |

4.1. Analysis of operational flexibility evaluation index

From the data in Table 1, the \(F_{\text{BFC}}^+\) is calculated to be 0.013, and the \(F_{\text{BFC}}^-\) is calculated to be 0.02. The flexibility index \(I_{\text{NFM},i}\) in an operation cycle is shown in Figure 2. It can be seen from the figure that the \(I_{\text{NFM}}\) of the access nodes (node 5, node 20, node 33) and their adjacent nodes of DG are low, the \(I_{\text{NFM}}\) of the nodes (node 18, node 33) at the end of the line (Node 5, Node 20, Node 33) is low, which indicates that the operational flexibility of these nodes is seriously insufficient. Since node 33 is both an end node of the line and an access node of DG, its \(I_{\text{NFM}}\) is the lowest, operational flexibility is seriously inadequate. The closer to the balance node, the larger the \(I_{\text{NFM}}\) and the greater operational flexibility will be. In addition, the distribution of \(I_{\text{NFM},i}\) of different nodes is different, indicating that
the operational flexibility of the distribution system has spatial characteristics.

Figure 2 (left) $I_{NFM,i}$ distribution of different nodes Figure 3 (right) $I_{SFM,t}$ distribution of different nodes

Figure 3 shows the distribution of $I_{SFM,t}$ with a time scale of 1h. As can be seen from the figure, $I_{SFM,t}$ has a large difference at different times. According to the distribution of $I_{SFM,t}$, its value is too small at time 7, 17, 18, 20, indicating that the system operational flexibility is seriously insufficient, which may cause overvoltage phenomenon, which will have a serious impact on system operation. At time 6, 13, 16, 19, the value of $I_{SFM,t}$ is small, and the system operation flexibility is insufficient. Compared with Figure 1 and DG output data, the following conclusion can be drawn: the operational flexibility at time 6 is insufficient because the PV starts to output. The main reason for the lack of operational flexibility at times 7, 16, 17, 18, 19 is that the DG output fluctuations are more severe. The reason for insufficient operational flexibility at time 13 is that the moment is the peak time of PV output during the operation day, and the number of nodes with unbalanced power or over-voltage in the system increases at this time. In summary, $I_{SFM,t}$ can screen out the time when operational flexibility is insufficient and quantify its severity, and then evaluate the distribution system operational flexibility from the time perspective.

4.2. Analysis of the influence of energy storage on operational flexibility

Before and after the energy storage devices put into the system, the distribution of $I_{NFM,i}$ and $I_{SFM,t}$ of some nodes are shown in Fig 4 and Fig 5.

Figure 4 (left) Distribution of $I_{NFM,i}$ before and after energy storage access Figure 5 (right) Distribution of $I_{SFC,t}$ before and after energy storage access

It can be seen from Figure 4 that after access of energy storage devices, the IBFC.I of the node (node 5) with insufficient operational flexibility and the nodes (node 20, node 33) with severely insufficient operational flexibility increase from 0.71, 0.67 and 0.42 to 1, 1 and 0.96, respectively. The operational flexibility of these nodes has been improved to a sufficient level. From Figure 5 it can be seen that when the energy storage device put into, the time when the operation flexibility is insufficient is obviously reduced, and the operational flexibility of the distribution system has been effectively improved. In summary, energy storage device can significantly improve the operational
flexibility of the power distribution system. In actual operation, the energy storage device can be arranged according to the abundance of operational flexibility. The voltage change before and after the energy storage is connected to the system is shown in Figure 6.

It can be seen from Figure 6 that energy storage access makes voltage fluctuations smaller, which can improve voltage and effectively achieve peak clipping, so energy storage can improve the operational flexibility of the distribution system.

![Figure 6](image_url)

(a) Before  
(b) After

Figure 6 Distribution of voltage amplitude before and after energy storage access

5. Conclusion
Aiming at the distribution system with high permeability DG, this paper analysed the relevant factors affecting the operation flexibility and used the improved fuzzy C-means clustering algorithm to cluster load scenarios. Considering the spatial structure and time scale of distribution system, the evaluation index and method of operation flexibility are proposed. By evaluating the operational flexibility of the improved IEEE33 distribution system, the following conclusions are drawn:

The operational flexibility evaluation index proposed in this paper can quantitatively evaluate the operational flexibility of the power distribution system, and can screen out the nodes and moments with insufficient operational flexibility. Placing energy storage devices at the access nodes of DG can significantly improve the operational flexibility of distribution system.

References
[1] WANG Chengshan, LI Peng, YU Hao 2018 *J. Automation of Electric Power Systems*, 42(10): 13-21.
[2] Lannoye E, Flynn D, O'Malley M 2012 *J. IEEE Transactions on Power Systems*, 27(2): 922-931.
[3] Yongliang Zhao, Peipei Fan, Chaoyang Wang 2019 *J. Applied Thermal Engineering*, 156.
[4] Wang L, Singh C 2008 *J. Electric Power Systems Research*, 78(8): 1361-1368.
[5] Zhao J, Zheng T, Litvinov E 2016 *J. IEEE Transactions on Power Systems*, 31(1): 339-347.
[6] Wang Haibing, Wang Chengmin et al. 2016 *J. Proceedings of the CSEE*, 36(24): 6838-6848+6939.