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ENHANCE FLEXIBILITY OF DISTRIBUTION SYSTEMS BY DYNAMIC NETWORK RECONFIGURATION

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ABSTRACT

How to enhance the ability of distribution systems to cope with the volatility of renewable energy sources and load, i.e. flexibility, has become a crucial issue for power system operation. In this paper, a two-stage robust model is proposed, which considers the volatility and uncertainty of renewable distributed generators and makes full use of dynamic reconfiguration to enhance the flexibility of distribution systems. Furthermore, several flexibility indexes are proposed to quantitatively evaluate the flexibility from the perspective of whole horizon and each period. Finally, the IEEE-33 system is used to test the validity of the proposed method.

Keywords: renewable distributed generation, distribution system flexibility, dynamic reconfiguration, robust optimization.

NOMENCLATURE

Sets/Indices	
$\boldsymbol{N}/N_{\text{bus}}$	Set/number of nodes
$\boldsymbol{L}/ij,js$	Set/indices of distribution lines
$\boldsymbol{T}/t$	Set/index of periods
$\boldsymbol{S}/N_{\text{sub}}$	Set/number of substations
$\boldsymbol{G}$	Set of DG units
$\boldsymbol{\delta}(j)$	Set of all children of node
$\boldsymbol{\pi}(j)$	Set of all parents of node
Parameters	
C_{RCS}	Cost factor of switching operation
C_{sub}	Cost factor of power purchase
C_{shed}	Cost factor of renewable energy shedding
C_{cut}	Cost factor of load cutting
U_j^0	Specified voltage value of node *j*
$P_{j,min}^{\text{sub}}/P_{j,max}^{\text{sub}}$	Minimum/Maximum active power limits of substation
$Q_{j,min}^{\text{sub}}/Q_{j,max}^{\text{sub}}$	Minimum/Maximum reactive power limits of substation
$P_{j,t}^{\text{load}}/Q_{j,t}^{\text{load}}$	Active/reactive load demand of node
$R_j^{\text{down}}/R_j^{\text{up}}$	Ramping-down/ramping-up limits of substation
r_{ij}/x_{ij}	Resistance/reactance of line
$U_j^{\min}/U_j^{\max}$	Minimum/maximum voltage limit of node
z_{ij}	Binary status, denotes the status of line equipped with a RCS
$K_{ij}^{\max}$	Maximum allowed number of line status changes
$S_{ij}^{\max}$	Maximum capacity of line
M	A large positive number
$\Delta P_{j,t}^{\text{RDG}}/\Delta Q_{j,t}^{\text{RDG}}$	Forecast error of renewable DG
Variables	
$P_{j,t}^{\text{sub}}/Q_{j,t}^{\text{sub}}$	Real/reactive power injection of substation
$H_{ij,t}/G_{ij,t}$	Active/reactive power of line
$\alpha_{ij,t}$	Binary variable, denotes the close flag of line
$\beta_{ij,t}$	Binary variable, denotes the open flag of line
$c_{ij,t}$	Binary variable, denotes the connection status of line
$P_{j,t}^{\text{shed}}/Q_{j,t}^{\text{shed}}$	Real/reactive power shedding of DG
$P_{j,t}^{\text{cut}}/Q_{j,t}^{\text{cut}}$	Real/reactive load cutting of node
$U_{j,t}$	Voltage value of node
$\tilde{P}_{j,t}^{\text{RDG}}/\tilde{Q}_{j,t}^{\text{RDG}}$	Uncertain active/reactive power of DG

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1. INTRODUCTION

As the penetration of renewable distributed generation (DG) increases in distribution systems worldwide, the operation of distribution systems becomes more and more complicated and variable. Therefore, it is necessary to fully schedule the existing resources to meet the real-time power balance, which requires distribution systems to be flexible enough to accommodate expected, as well as unexpected, changes in system operating conditions [1].

North American Electric Reliability Council (NERC) defines flexibility as the ability to use system resources to meet load's uncertainty [2]. In [3], the concepts of power system flexibility, indices of flexibility and implementation of flexibility in power system security are summarized and discussed. Four elements, namely, time, uncertainty, action, and cost, are identified to evaluate flexibility of power systems in [4]. In the related research of flexibility assessment, [5] proposes insufficient ramping resource expectation (IRRE) metric to measure power system flexibility in long-term planning. An improved linear formulation of unit commitment model to evaluation of the renewable energy shedding and operational costs is proposed in [6]. The studies on flexibility above are all carried out in transmission systems and only consider the flexibility provided by generators.

Unlike transmission systems, the variation of network topology is a basic characteristic of distribution systems. According to the distribution system operation time frame, network reconfiguration can be classified as static reconfiguration and dynamic reconfiguration [7]. In comparison with static reconfiguration, dynamic reconfiguration can change the network hourly through pre-equipped remotely controlled switches (RCSs), and then the load supply path, system power flow and the relative position of DG are changed. It is more effective to deal with the uncertainty and variability of renewable DG and thus improve the flexibility of distribution systems. Therefore, how to make full use of dynamic network reconfiguration to enhance the ability of distribution systems to cope with the volatility of renewable DG and load is a crucial issue. Up to the authors' knowledge, there is little research on this subject. The main contributions of this paper are as follows: 1) A two-stage robust optimization model is proposed to enhance the flexibility of distribution systems by dynamic reconfiguration. 2) A set of flexibility indexes are proposed, which can quantitatively evaluate the flexibility of distribution systems during the evaluation horizon and at each period.

2. FLEXIBILITY ENHANCEMENT MODEL AND FLEXIBILITY INDEXES

In this section, a two-stage robust optimization model to enhance the flexibility of distribution systems is introduced in detail. Then, based the proposed model, several indexes for flexibility assessment are further proposed.

2.1 Objective Function

Considering the flexibility of sources and networks, only the operation cost of RCS and substation is included. Take one day as scheduling cycle, and the maintenance cost of equipments and lines are not considered in this model. The objective function is defined as Eq.(1).

$$\text{MOC}=\min_{x\in\boldsymbol{\Omega}}(C_{\text{RCS}}^{\text{total}}+\max_{u\in\boldsymbol{\Phi}}\min_{y\in\boldsymbol{\Psi}(x,u)}(C_{\text{sub}}^{\text{total}}+C_{\text{penalty}}^{\text{total}})) \tag{1}$$

Where,

$$C_{\text{RCS}}^{\text{total}}=\sum_{ij\in\boldsymbol{L}}\sum_{t\in\boldsymbol{T}}C_{\text{RCS}}(\alpha_{ij,t}+\beta_{ij,t}) \tag{2}$$

$$C_{\text{sub}}^{\text{total}}=\sum_{j\in\boldsymbol{S}}\sum_{t\in\boldsymbol{T}}C_{\text{sub}}P_{j,t}^{\text{sub}} \tag{3}$$

$$C_{\text{penalty}}^{\text{total}}=\sum_{j\in\boldsymbol{N}}\sum_{t\in\boldsymbol{T}}C_{\text{shed}}P_{j,t}^{\text{shed}}+C_{\text{cut}}P_{j,t}^{\text{cut}} \tag{4}$$

$C_{\text{RCS}}^{\text{total}}$ is the cost of switching operation. $C_{\text{sub}}^{\text{total}}$ refers to the power purchase cost from transmission systems. $C_{\text{penalty}}^{\text{total}}$ is the penalty cost of reluctant renewable energy shedding and load cutting to maintain power balance in the worst case. Vectors x, y and u represent the binary variables, continuous variables and uncertainty variables respectively, where x = [$\alpha_{ij,t}$; $\beta_{ij,t}$; $c_{ij,t}$], y = [$P_{j,t}^{\text{sub}}$; $Q_{j,t}^{\text{sub}}$; $U_{j,t}$; $H_{ij,t}$; $G_{ij,t}$; $P_{j,t}^{\text{shed}}$; $Q_{j,t}^{\text{shed}}$; $P_{j,t}^{\text{cut}}$; $Q_{j,t}^{\text{cut}}$] and u = [$\tilde{P}_{j,t}^{\text{RDG}}$; $\tilde{Q}_{j,t}^{\text{RDG}}$]. Their feasible regions are denoted as $\boldsymbol{\Omega}$, $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}(x, u)$, which are defined by constraints (12)-(16), the given interval of $\tilde{P}_{j,t}^{\text{RDG}}$ and $\tilde{Q}_{j,t}^{\text{RDG}}$, and constraints (5)–(11) respectively.

2.2 Constraints

2.2.1 Operation Constraints

Linearized DistFlow is applied to formulate operation constraints of distribution systems, as (5)-(11).

$$\begin{gathered}\tilde{P}_{j,t}^{\text{RDG}}+P_{j,t}^{\text{sub}}-P_{j,t}^{\text{load}}+P_{j,t}^{\text{cut}}-P_{j,t}^{\text{shed}}=\sum_{s\in\delta(j)}H_{js,t}-\sum_{i\in\pi(j)}H_{ij,t}\\ \forall j\in\boldsymbol{N},\forall t\in\boldsymbol{T},\forall\tilde{P}_{j,t}^{\text{RDG}}\in[\bar{P}_{j,t}^{\text{RDG}}-\Delta P_{j,t}^{\text{RDG}},\bar{P}_{j,t}^{\text{RDG}}+\Delta P_{j,t}^{\text{RDG}}]\end{gathered} \tag{5}$$

$$\begin{gathered}\tilde{Q}_{j,t}^{\text{RDG}}+Q_{j,t}^{\text{sub}}-Q_{j,t}^{\text{load}}+Q_{j,t}^{\text{cut}}-Q_{j,t}^{\text{shed}}=\sum_{s\in\delta(j)}G_{js,t}-\sum_{i\in\boldsymbol{\pi}(j)}G_{ij,t}\\ \forall j\in\boldsymbol{N},\forall t\in\boldsymbol{T},\forall\tilde{Q}_{j,t}^{\text{RDG}}\in[\bar{Q}_{j,t}^{\text{RDG}}-\Delta Q_{j,t}^{\text{RDG}},\bar{Q}_{j,t}^{\text{RDG}}+\Delta Q_{j,t}^{\text{RDG}}]\end{gathered} \tag{6}$$

$$\begin{cases} -S_{ij}^{\max} c_{ij,t} \le H_{ij,t} \le S_{ij}^{\max} c_{ij,t} \\ -S_{ij}^{\max} c_{ij,t} \le G_{ij,t} \le S_{ij}^{\max} c_{ij,t} \end{cases} \quad \forall ij \in \boldsymbol{L}, \forall t \in \boldsymbol{T} \tag{7}$$

$$\begin{cases} P_{j,\min}^{\text{sub}} \le P_{j,t}^{\text{sub}} \le P_{j,\max}^{\text{sub}} \\ Q_{j,\min}^{\text{sub}} \le Q_{j,t}^{\text{sub}} \le Q_{j,\max}^{\text{sub}} \end{cases} \quad \forall t \in \boldsymbol{T}, \forall j \in \boldsymbol{S} \tag{8}$$

$$-R_j^{\text{down}} \le P_{j,t}^{\text{sub}} - P_{j,t-1}^{\text{sub}} \le R_j^{\text{up}} \quad \forall t \in \boldsymbol{T}, \forall j \in \boldsymbol{S} \tag{9}$$

$$\begin{cases} U_{i,t} - U_{j,t} \ge -M(1-c_{ij,t}) + \dfrac{r_{ij} H_{ij,t} + x_{ij} G_{ij,t}}{U_0} \\ U_{i,t} - U_{j,t} \le M(1-c_{ij,t}) + \dfrac{r_{ij} H_{ij,t} + x_{ij} G_{ij,t}}{U_0} \end{cases} \quad \begin{matrix} \forall j \in \boldsymbol{N} \\ \forall t \in \boldsymbol{T} \\ \forall ij \in \boldsymbol{L} \end{matrix} \tag{10}$$

$$U_j^{\min} \le U_{j,t} \le U_j^{\max} \quad \forall j \in \boldsymbol{N}, \forall t \in \boldsymbol{T} \tag{11}$$

$\tilde{P}_{j,t}^{\text{RDG}}$ and $\tilde{Q}_{j,t}^{\text{RDG}}$ are uncertain variables that represent the active power and reactive power outputs of renewable DG j in period t. Eq. (5) and (6) are the active and reactive power balance equation respectively. They must be satisfied for any value of $\tilde{P}_{j,t}^{\text{RDG}}$ and $\tilde{Q}_{j,t}^{\text{RDG}}$ in a given interval. Therefore, the proposed model is a robust optimization model. (7) is capacity limit of line ij; (8) and (9) refer to the output limit and ramp limit of each substation; (10) refers to the DistFlow equation and (11) refers to voltage limit of each bus. In (10), if the branch is closed, the voltage difference of this branch is constrained by power flow and the branch flow should be limited, otherwise, the voltage difference is arbitrary and the branch flow must be zero.

2.2.2 Topology Constraints

In normal operation of distribution systems, topology constraints are modeled as follows to ensure network radiality at each period.

$$\sum_{ij \in \boldsymbol{L}} c_{ij,t} = N_{\text{bus}} - N_{\text{sub}} \quad \forall t \in \boldsymbol{T} \tag{12}$$

$$c_{ij,t-1} - z_{ij} \le c_{ij,t} \le c_{ij,t-1} + z_{ij} \quad \forall t \in \boldsymbol{T}, \forall ij \in \boldsymbol{L} \tag{13}$$

$$\alpha_{ij,t} - \beta_{ij,t} = c_{ij,t} - c_{ij,t-1} \quad \forall t \in \boldsymbol{T}, \forall ij \in \boldsymbol{L} \tag{14}$$

$$\alpha_{ij,t} + \beta_{ij,t} \le 1 \tag{15}$$

$$\sum_{t \in \boldsymbol{T}} (\alpha_{ij,t} + \beta_{ij,t}) \le K_{ij,\max} \quad \forall ij \in \boldsymbol{L} \tag{16}$$

Where, Eq.(12) is to ensure the radiality of the distribution network. In (13), if the branch *ij* is equipped with a RCS switch, then z_{ij}=1, the status of branch *ij* can be changed over the horizon. If the branch *ij* is equipped with a manual switch, then z_{ij}=0. Once the status of branch *ij* is determined before the dispatch horizon, it cannot be changed over the horizon. The equality constraint of switch status can be expressed as (14). $\alpha_{ij,t}$ and $\beta_{ij,t}$ are limited by (15), so that for each period, only one of them can be equal to 1. Constraint (16) limits the number of actions of branch *ij* to avoid frequent changes of network topology.

2.3 Flexibility evaluation indexes

Distribution systems require enough flexibility to respond to uncertainty of renewable energy timely over different time scales. Flexibility includes upward flexibility and downward flexibility. If distribution systems can't deploy existing resources in time to cope with a suddenly drop of renewable energy output, the loads of distribution systems should be cut to maintain real-time power balance. This load cutting operation is caused by insufficient upward flexibility. Similarly, if distribution systems are not of enough downward flexibility, which means the systems can't timely deploy existing resources to cope with the suddenly increase of renewable energy output, the operation of shedding renewable energy will be carried out. Therefore, this paper proposes a set of flexibility evaluation indexes that reflect the upward and downward flexibility during the evaluation horizon and at each period, as (17)-(20).

$$\text{Flex}_{\text{system}}^{\text{up}} = \frac{\sum_{t \in \boldsymbol{T}} \sum_{j \in \boldsymbol{N}} (P_{j,t}^{\text{load}} - P_{j,t}^{\text{cut}})}{\sum_{t \in \boldsymbol{T}} \sum_{j \in \boldsymbol{N}} P_{j,t}^{\text{load}}} \tag{17}$$

$$\text{Flex}_{\text{system}}^{\text{down}} = \frac{\sum_{t \in \boldsymbol{T}} \sum_{j \in \boldsymbol{G}} (\tilde{P}_{j,t}^{\text{RDG}} - P_{j,t}^{\text{shed}})}{\sum_{t \in \boldsymbol{T}} \sum_{j \in \boldsymbol{G}} \tilde{P}_{j,t}^{\text{RDG}}} \tag{18}$$

$$\text{Flex}_t^{\text{up}} = \frac{\sum_{j \in \boldsymbol{N}} (P_{j,t}^{\text{load}} - P_{j,t}^{\text{cut}})}{\sum_{j \in \boldsymbol{N}} P_{j,t}^{\text{load}}} \quad \forall t \in \boldsymbol{T} \tag{19}$$

$$\text{Flex}_t^{\text{down}} = \frac{\sum_{j \in \boldsymbol{G}} (\tilde{P}_{j,t}^{\text{RDG}} - P_{j,t}^{\text{shed}})}{\sum_{j \in \boldsymbol{G}} \tilde{P}_{j,t}^{\text{RDG}}} \quad \forall t \in \boldsymbol{T} \tag{20}$$

The physical meaning of equation (17)-(20) are supply rate of system load and the utilization rate of system renewable energy during the horizon and at each period, which indicate the ability of upward and downward flexibility of distribution systems. The value range of the indexes is [0, 1]. The larger the value, the more flexible the system is, and 1 indicates that the system is flexible enough. By calculating the $\text{Flex}_t^{\text{up}}$ and $\text{Flex}_t^{\text{down}}$, we can obtain the evaluation index sequences as (21) and (22). In this way, the expectation of upward and downward flexibility and the rate of insufficient flexibility period are defined as (23)-(24) and (25)-(26).

$$\text{Flex}^{\text{up}} = \left\{ \text{Flex}_1^{\text{up}}, \text{Flex}_2^{\text{up}}, \ldots, \text{Flex}_{\text{T}}^{\text{up}} \right\} \tag{21}$$

$$\mathrm{Flex}^{\mathrm{down}}=\left\{\mathrm{Flex}_1^{\mathrm{down}},\mathrm{Flex}_2^{\mathrm{down}},...,\mathrm{Flex}_T^{\mathrm{down}}\right\} \tag{22}$$

$$\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{up}}=\frac{1}{\mathrm{T}}\sum_{t\in\boldsymbol{T}}\mathrm{Flex}_t^{\mathrm{up}} \tag{23}$$

$$\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{down}}=\frac{1}{\mathrm{T}}\sum_{t\in\boldsymbol{T}}\mathrm{Flex}_t^{\mathrm{down}} \tag{24}$$

$$\mathrm{Rate}_{\mathrm{system}}^{\mathrm{up}}=\frac{1}{\mathrm{T}}\sum_{t\in\boldsymbol{T}}\delta_t^{\mathrm{up}} \tag{25}$$

$$\mathrm{Rate}_{\mathrm{system}}^{\mathrm{down}}=\frac{1}{\mathrm{T}}\sum_{t\in\boldsymbol{T}}\delta_t^{\mathrm{down}} \tag{26}$$

Where, δ_t^{up}, and δ_t^{down} are binary variables. If $\mathrm{Flex}_t^{\mathrm{up}}$=1, δ_t^{up} =0; Otherwise， δ_t^{up} =1. If $\mathrm{Flex}_t^{\mathrm{down}}$ =1, δ_t^{down} =0, Otherwise， δ_t^{down}=1.

To sum up, the proposed two-stage RO model is given as (1)-(16). The first stage determines the network topology. The second stage determines the operation modes. The C&CG algorithm[8] is applied to solve the proposed model, as shown in Fig 1. Various metrics for flexibility assessment as shown in (17)-(26) can therefore be calculated based on these results.

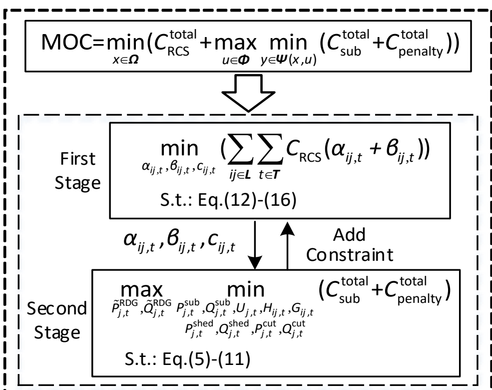

Fig 1 Flowchart for the solution of the two-stage robust model

3. CASE STUDY

3.1 Test System

As shown in Fig 2, the IEEE 33-node distribution system is used to demonstrate the proposed method. The system operates at the voltage level of 12.66 kV. Minimum and maximum voltage limits are set as 0.95 p.u. and 1.05 p.u. Details of this test system can be found in [9]. The maximum capacity and ramp rate of substation are 3 MW and 600 kW/h. The power factor of all DG types is considered to be 0.85. The maximum capacities of DG at different penetration are listed in TABLE I. The cost factor of power purchase and switching operation are set 0.2\$/kW·h and 5\$/time respectively. The cost factor of renewable energy shedding and load cutting are set 10\$/kW·h and 200\$/kW·h respectively. There are 7 lines equipped with RCS switches, which are L7, L12, L16, L20, L25, L27 and L34, and the maximum number of actions of each RCS switch is set to 4.

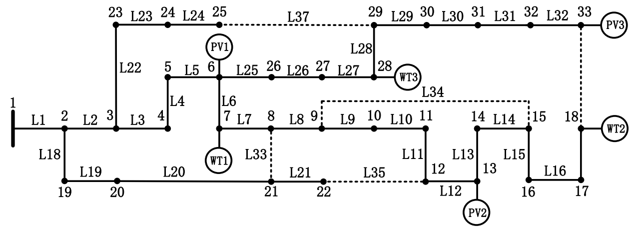

Fig 2 The modified IEEE 33-node distribution system

3.2 Results

Dynamic reconfiguration can change the network topology hourly and is beneficial to the time varying nature of DG. In order to study the important role of dynamic reconfiguration to system flexibility, two cases are presented to test the proposed method. Case 1, considering dynamic reconfiguration. For this case, day-ahead status of manual switches and real-time status of RCSs can be optimized. Then, the hourly network topology is determined. In Case 2, no reconfiguration is considered. The results in different forecast errors are shown in TABLE II and TABLE III.

TABLE I THE MAXIMUM CAPACITY OF DG

Penetration	Bus 6	Bus 7	Bus 13	Bus 18	Bus 28	Bus 33
65%	500	300	500	600	600	400
75%	400	500	600	700	700	400
85%	500	600	600	800	800	500

TABLE II THE RESULTS OF FLEXIBILITY INDEXES

Case	Flex	Forecast errors			
		30%	25%	20%	15%
Case 1	$\mathrm{Flex}_{\mathrm{system}}^{\mathrm{up}}$	0.9824	0.9854	0.9908	0.9936
	$\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{up}}$	0.9877	0.9908	0.9941	0.9959
	$\mathrm{Flex}_{\mathrm{system}}^{\mathrm{down}}$	0.6256	0.6736	0.7014	0.7323
	$\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{down}}$	0.7507	0.7780	0.7901	0.8133
Case 2	$\mathrm{Flex}_{\mathrm{system}}^{\mathrm{up}}$	0.9663	0.9717	0.9771	0.9824
	$\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{up}}$	0.9780	0.9815	0.9849	0.9883
	$\mathrm{Flex}_{\mathrm{system}}^{\mathrm{down}}$	0.5051	0.5435	0.5844	0.6256
	$\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{down}}$	0.5742	0.6038	0.6371	0.6724

Taking 75% penetration and 25% forecast error of DG as an example, the downward flexibility of Case 1 and Case 2 for each period are shown in Fig 2.

From TABLE II, the value of $\mathrm{Flex}_{\mathrm{system}}^{\mathrm{up}}$, $\mathrm{Flex}_{\mathrm{system}}^{\mathrm{down}}$, $\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{up}}$ and $\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{down}}$ in Case 1 are larger than those in Case 2, indicating that dynamic reconfiguration plays a positive role in improving the flexibility of distribution systems. Since the $\mathrm{Flex}_{\mathrm{system}}^{\mathrm{up}}$ and $\mathrm{Flex}_{\mathrm{system}}^{\mathrm{down}}$ are calculated from the perspective of whole system, while $\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{up}}$ and $\mathrm{Flex}_{\mathrm{expect}}^{\mathrm{down}}$ from the perspective of each period. There are some differences in the value of two types of indexes. The system considering dynamic reconfiguration has sufficient flexibility at the period of 1, 4, 19, 21 and 24 in Fig 3. Therefore, the rate of insufficient downward flexibility is reduced, as shown in TABLE III.

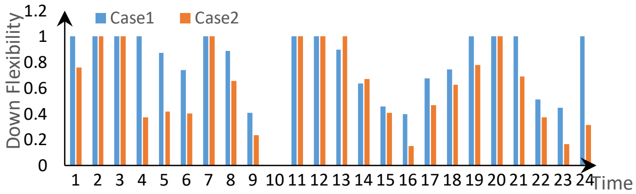

Fig 3 The comparison of the downward flexibility sequence

TABLE III THE RATE OF INSUFFICIENT FLEXIBILITY

Case	Flex	Forecast errors			
		30%	25%	20%	15%
Case 1	$Rate^{up}_{system}$	0.2500	0.2500	0.1667	0.1667
	$Rate^{down}_{system}$	0.6250	0.5417	0.5833	0.5417
Case 2	$Rate^{up}_{system}$	0.1667	0.1250	0.1250	0.1250
	$Rate^{down}_{system}$	0.7083	0.7083	0.7083	0.7083

The expectation of upward and downward flexibility under different DG penetration and forecast errors are shown in Fig 4. With the increases of the penetration and forecast errors of DG, the dynamic reconfiguration improves the system flexibility more obviously. In the worst case, the renewable energy shedding operation is prioritized to maintain real-time power balance due to the value of C_{shed} and C_{cut}. The expectation of downward flexibility is more sensitive to dynamic reconfiguration. In addition, we can conclude that the smaller the forecast error, the better the expectation of flexibility of system.

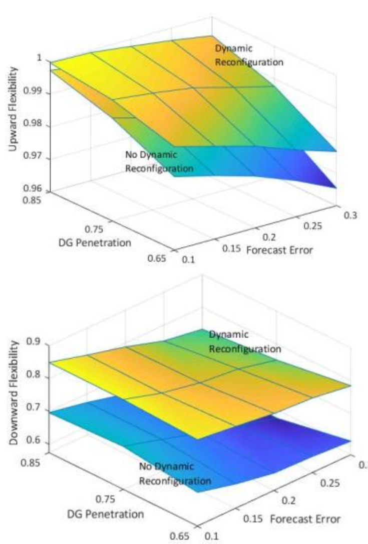

Fig 4 The expectation of upward and downward flexibility

4. CONCLUSIONS

The high penetration of renewable DG poses higher requirements for the flexibility of distribution systems. A two-stage robust model for enhancing distribution system flexibility is proposed, in which dynamic reconfiguration is fully used to improve the operation flexibility of distribution systems.

The results show that dynamic reconfiguration is an important flexibility resource that can improve ability of distribution systems to cope with the volatility of renewable DG and load significantly. In addition, the higher penetration and greater the forecast error, the more obvious effect of dynamic reconfiguration for improving flexibility.

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