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DYNAMIC RECONFIGURATION METHOD OF DISTRIBUTION NETWORK BASED ON VOLTAGE FLUCTUATION DEVIATION OF TIME INTERVALS

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ABSTRACT

Aiming at the economical and safe operation of distribution networks with high permeability of distributed wind power generations, a dynamic reconfiguration method based on voltage fluctuation deviation is proposed. Firstly, in order to reduce the continuous action of the switch in a short time, a single switch operation cost model is constructed and introduced into the distribution network dynamic reconfiguration model in the form of a similar penalty function. Then, the voltage fluctuation deviation index of the distribution network node is proposed. It can characterize the development trend of the overall state of the distribution network. According to the magnitude and time series distribution of the voltage fluctuation deviation value, the reconstructed time division result can be obtained intuitively. Finally, the speed and location update mechanism has been improved to overcome the limitations of the traditional binary particle swarm reconfiguration. Results of calculation example show that the proposed method is efficient and effective.

Keywords: wind power; dynamic reconfiguration; time division; voltage fluctuation deviation; improved binary particle swarm optimization

1. INTRODUCTION

High-permeability distributed renewable energy generation has become a widely accepted future distribution system scenario. In this scenario, how to realize the economic operation of the distribution system and improve the safety of the distribution network through the dynamic reconfiguration of the distribution system has become one of the key issues affecting the improvement of operation level of distribution system in the future. Generally, the dynamic reconfiguration problem is decomposed into two sub-problems to solve: (1) time division sub-problem(T-problem): based on certain rules or practical operation experience, the whole reconfiguration period is divided into periods, and the dynamic reconfiguration problem is transformed into a combination of static reconfiguration problems in a series of subdivided periods; (2) multi-period static reconfiguration sub-problem(M-problem): based on time division result, solve the static reconfiguration problem in each period, and form an overall dynamic reconfiguration scheme. T-problem is the foundation and key of dynamic reconfiguration problem. Some literatures firstly divide the period into equal parts, and then merge them with certain rules such as [1]. Others firstly specify indicators, such as the ratio of active network loss to voltage deviation [2], power moment [3], and then guide the time division through the index values. Others cluster the initial data and then divide the time into periods [4]. Some scholars have also studied the dynamic reconfiguration of distribution network with distributed power supply. However, most of the current time division methods can only reflect the overall load of the distribution network or the output of the distributed power supply, and the ability to reflect the state changes of the nodes in distribution network is not strong.

In this paper, the index of voltage fluctuation deviation is proposed to measure whether the overall state of the distribution network changes during each period, so as to guide the time division. The objective function of this paper is the minimum comprehensive operation cost in the whole operation cycle, and the constraint condition is to meet the security constraints under various scenarios of the wind power output. At the initial moment of each time period, the improved binary particle swarm optimization (BPSO) algorithm is used to reconstruct and obtain the optimal reconfiguration scheme. Finally, the effectiveness of the model and method is verified by IEEE 33-node example.

2. CONSTRUCTION OF DISTRIBUTION NETWORK RECONFIGURATION MODEL BASED ON TIME DIVISION

2.1 Wind power generation model

The output power of a wind turbine is mainly determined by the wind speed of the fan blades.The simplified output power function of wind turbine is expressed as follows :

$$P(v)=\begin{cases}0 & (v<v_{ci}, v>v_{co}) \\ k_1 v+k_2 & (v_{ci}\le v<v_r) \\ P_r & (v_r\le v<v_{co})\end{cases} \tag{1}$$

In the formula, v_{ci}, v_r and v_{co} are respectively wind turbine cut-in wind speed, rated wind speed and cut-out wind speed; P_r is rated power; $k_1 = P_r/(v_r-v_{ci})$ and $k_2=-k_1v_{ci}$ are coefficients. This paper assumes that the wind turbine can operate at a constant power factor $\cos\varphi$, so its reactive power output is as follows:

$$Q(v)=P(v)\tan\varphi \tag{2}$$

For wind power output prediction, the actual wind power forecasting error is relatively large. Considering that wind speed prediction error is the main reason for wind power prediction error[5], this paper uses the probability density function of wind speed error distribution to predict wind power output prediction error. In terms of scene generation, the latin hypercube sampling method is selected to obtain a multi-scenario sample that guarantees the sampling validity and representative for wind power output.

2.2 Distribution network dynamic reconfiguration model

The dynamic reconfiguration of this paper aims to minimize the comprehensive operating cost which consists the network loss cost and the switch operation cost of the distribution network during the whole time period. The objective function is:

$$\min F=\sum_{i=1}^{N}B_{pi}P_{i,k}\Delta t_i p_k+\sum_{j=1}^{NB}\sum_{k=1}^{M}B_{s,k}\left|s_{j,k}-s_{j,k-1}\right| \tag{3}$$

In the formula, F is the comprehensive operating cost of the distribution network for the whole time period; N is the total number of time points before the time division, and generally $N=24$ *in* a typical day; M is the total number of time periods after the time division; B_{pi} is The electricity price of the period i; $P_{i,k}$ is the active network loss of the distribution network in the period i of the scene k; p_k is the proportion of the scene k in all the scenes; Δt_i is the duration of the period i; NB is the total number of operable switches; $B_{s,k}$ is the cost of operating a switch; $s_{j,k}$ is the state of switch j at time period k, where 0 indicates that the switch is open and 1 indicates that the switch is closed.

The operation of the distribution network needs to avoid frequent operation of the switch in a short time. In this paper, the single switch operation cost is functionalized and added to the objective function in the form of a similar penalty function. The single switch operation cost model is：

$$B_{s,k}=B_s(1-2x)^{10} \tag{4}$$

$$x=\begin{cases}\left|s_{j,k}-s_{j,k-1}\right|+\left|s_{j,k-1}-s_{j,k-2}\right|+\ldots+\left|s_{j,k-D+1}-s_{j,k-D}\right| & k\ge D \\ \left|s_{j,k}-s_{j,k-1}\right|+\left|s_{j,k-1}-s_{j,k-2}\right|+\ldots+\left|s_{j,2}-s_{j,1}\right| & k\le D\end{cases} \tag{5}$$

Where: B_s is the standard cost of a single operation of the switch; x is the number of switching operations within a specified short interval; D is the specified short interval. If $B_s = 7$ and $D = 5$, the single operation cost of the switch as shown in Table 1 can be obtained.

Tab 1 Switch operation cost

Operation times	1	2	3	4	5
Single operation cost($)	7	$3.0*10^5$	$4.9*10^7$	$1.4*10^9$	$1.74*10^{10}$

It can be seen that when the switch is continuously operated within the specified time, the single operation cost increases sharply, and the target function value will increase, so that it can be prevented from being selected in the optimization.

After reconfiguration, the network should satisfy the radial network topology constraints and the power flow equation constraints. In addition, the node voltage constraint, the branch transmission power constraint, and the number constraint of operations of single switch and all switches should be met [3].

2.3 Time division based on voltage fluctuation deviation

At present, the time division of the dynamic reconfiguration of the distribution network is generally based on the load data of the all-day system at 24 or 48 time points. This article refers to the concept of derivatives, extending it to discrete voltage points and defining them as follows

$$\mathbf{V}_t^T=\{v_{1,t}, v_{2,t}, \ldots, v_{n,t}\} \tag{6}$$

$$\Delta v_{i,t}=v_{i,t}-v_{i,t-1} \tag{7}$$

$$\Delta\mathbf{V}_t^T = \left\{\Delta v_{1,t}, \Delta v_{2,t}, ..., \Delta v_{n,t}\right\} \tag{8}$$

$$\Delta\mathbf{V} = \left\{\Delta\mathbf{V}_1, \Delta\mathbf{V}_2, ..., \Delta\mathbf{V}_N\right\} \tag{9}$$

Where: $\boldsymbol{V_t}$ is the node voltage vector at time *t*; $v_{i,t}$ is the voltage amplitude of node *i* at time *t*; $\Delta v_{i,t}$ is the variation of node *i* voltage at time *t* relative to time *t-1*; $\boldsymbol{\Delta V_t}$ is the node voltage variation vector of *t* time relative to time *t-1*; $\boldsymbol{\Delta V}$ is the total node voltage variation matrix; *n* is the total number of nodes; *N* is the total number of time points before the time division.

Node voltage state of distribution network can reflect the operation status of distribution network. The variation of node voltage between adjacent points ($\Delta v_{i,t}$) reflects the speed and direction of node voltage change in distribution network. Due to the difference in the direction of the node voltage change, directly squaring and summing the voltage changes of all nodes at the same time will neglect the changing direction of the node voltage. Therefore, in order to reduce the impact of the direction of node voltage change, this paper defines the relative variation of node voltage as follows:

$$v_t' = \min\left(\Delta\mathbf{V}_t\right) = \min\left\{\Delta v_{1,t}, \Delta v_{2,t}, ..., \Delta v_{n,t}\right\}^T \tag{10}$$

$$\Delta\bar{v}_{i,t} = \Delta v_{i,t} - v_t' \tag{11}$$

$$\Delta\bar{\mathbf{V}}_t^T = \left\{\Delta\bar{v}_{1,t}, \Delta\bar{v}_{2,t}, ..., \Delta\bar{v}_{n,t}\right\} \tag{12}$$

Where: v_t' is the minimum value of the change of all node voltages at *t* time relative to *t-1*; $\Delta\bar{v}_{i,t}$ is the relative variation of voltage of all nodes at *t* time relative to *t-1*; $\boldsymbol{\Delta\bar{V}_t}$ is the vector of the relative variation of the node voltage.

In order to find out the time when the voltage of the distribution network node changes greatly, this paper squares voltage relative change of each node at time *t* and sums them, and the obtained value is expressed as the index *E(t)* reflecting whether the overall state of the distribution network changes. Define this value *E(t)* as the **voltage fluctuation deviation** (VFD).

$$E(\mathrm{t}) = \left\|\Delta\bar{\mathbf{V}}_t\right\|^2 = \Delta\bar{\mathbf{V}}_t^T\Delta\bar{\mathbf{V}}_t = \sum_{i=1}^{n}\left(\Delta\bar{v}_{i,t}\right)^2 \tag{13}$$

It can be seen that at time *t*, when the overall state of the distribution network does not change relative to the previous point, *E(t)*=0; when the overall state of the distribution network changes, *E(t)*>0, and the change is greater, the *E(t)* is larger.

In this paper, the time division is performed according to the above-mentioned VFD value. The time point where *E(t)* is the largest is selected as the reconfiguration starting point of each time period after the division. The number of specific time points can be determined according to site requirements. For example, when the dynamic reconfiguration speed is required to be fast, the number of selected time points can be reduced; when the overall scheme is required to be optimal, the number of selected time points can be increased.

3. RECONFIGURATION METHOD BASED ON IMPROVED BPSO

Considering the radial constraint characteristics of the distribution network and the optimization effect of BPSO is not ideal, this paper improves the model as follows.

3.1 Improvement of speed update mechanism

Referring to the differential evolution algorithm mutation operation, modify the BPSO speed update mechanism as follows:

$$v_{q,d}^k = \omega v_{q,d}^{k-1} + c_1 r_1\left(p_{q,d}^{k-1} - x_{q,d}^{k-1}\right) + c_2 r_2\left(g_d^{k-1} - x_{q,d}^{k-1}\right) + c_3 r_3\left(p_{i,d}^{k-1} - p_{j,d}^{k-1}\right) \tag{14}$$

Where: $v^k_{q,d}$ is the speed of the d-dimension of the *q*-th particle at the *k-th* iteration; ω is the inertia weight; c_1, c_2, c_3 are the individual, global and random learning factors respectively; r_1, r_2, r_3 are random number between [0,1]; $p^{k-1}_{q,d}$, g^{k-1}_d and $x^{k-1}_{q,d}$ is the historical optimal position, global optimal position and current position of the d-dimension of the *q*-th particle after *k-1* iteration; *i*, *j* is a random number between 1 and the total number of particles.

3.2 Improvement of position update mechanism

In order to ensure that each particle in the iteration satisfies the radial constraint and maintain the overall optimization effect of the particle swarm, this paper uses the stepping principle and the broken circle method to improve the position iteration formula.

$$\begin{cases} x_{q,d}^k = 1, x_{q,d}^{k-1} = 0, v_{q,d}^k = \max\left(\forall v_{q,i}^k\right) \\ x_{q,d}^k = 0, x_{q,d}^{k-1} = 1, v_{q,d}^k = \min\left(\forall v_{q,L}^k\right), d \in L \end{cases} \tag{15}$$

In the formula: $x^k_{q,d}$ is the d-dimensional state of the *q-th* particle in the *k-th* iteration; $\forall v^{k-1}_{q,i}$ is the change speed of the dimension where all the states of the *q-th* particle are zero in the *k-th* iteration; $v^k_{q,L}$ is the velocity of all dimensions in the *k-th* iteration; $d \in L$ means that after the switch is closed, the loop L includes the d-dimension; $\forall v^k_{q,L}$ is the speed of all dimensions at the *k-th* iteration of the loop L.

The flow of the improved algorithm is shown in Figure 1.

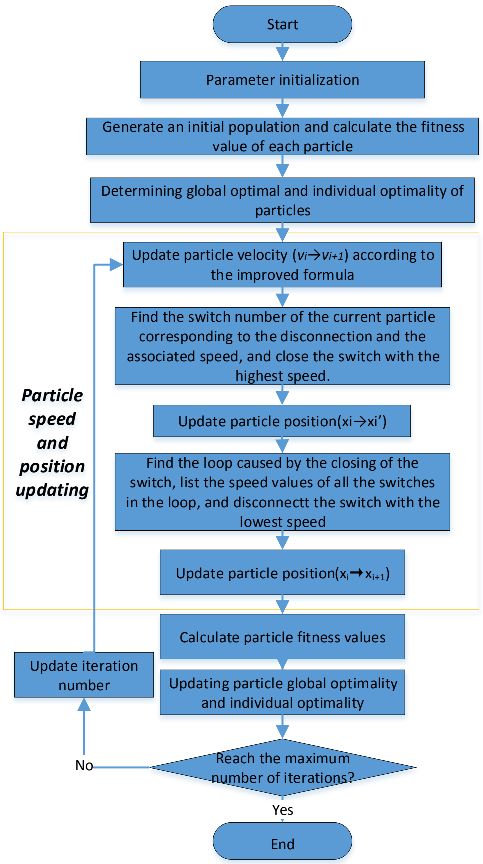

Fig 1 Flow chart of improved BPSO algorithm

4. CASE VERIFICATION

4.1 Introduction to the case

This paper uses the IEEE 33-node power distribution system for case analysis (Figure 2). The system reference voltage is 12.66 kV and the reference power is 10 MVA. The total network load of the system is 3715+j2300kVA. One day's load data can be referred to in [6].This chapter simulates and analyzes the following three aspects:

(1) Using the standard IEEE 33-node example, the performance of the improved BPSO is verified by the static reconfiguration method with the minimum network loss as the objective function;

(2) Using the standard IEEE 33-node example, the method of this paper is used to dynamically reconstruct the traditional passive distribution network. The applicability is verified by comparison with other literatures;

(3) Using the modified IEEE 33-node example, the method of this paper is used to dynamically reconstruct the distribution network considering distributed wind power, and the applicability will be verified.

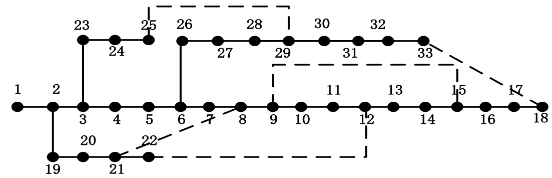

Fig 2 IEEE 33-node distribution feeder system

4.2 Efficiency verification of distribution network reconfiguration algorithm

The reconfiguration parameters of this paper are: population size is 50, maximum iteration number is 30, inertia constant ω=1, learning factor c_1=2, c_2=1, c_3=2.

The calculation results of **optimization success rate** are shown in Table 2. The results show that the improved BPSO has obvious advantages in the global optimization success rate compared with the traditional BPSO [7].

Tab 2 Optimization success rate comparison

Algorithm	The maximum number of iterations	Population size	Global optimal success rate
Traditional BPSO	30	50	34%
Improved BPSO	30	50	98%

The number of power flow calculations in the reconfiguration process is used as a comparison criterion for **optimization efficiency**. The results are shown in Table 3. The results show that compared with traditional BPSO and other intelligent algorithms, the algorithm propsed in this paper also has certain advantages.

Tab 3 Optimization efficiency comparison

Algorithm	power flow calculation numbers
Traditional BPSO	1250
Fuzzy genetic algorithm	1780
Simulated annealing + ant colony algorithm	1050
Improved BPSO	568

4.3 Dynamic reconfiguration of traditional passive distribution network scenes

Assume that the maximum number of actions of a single switch is 3, the number of all switching operations is limited to 15 times, the maximum number of reconfigurations is four, the switching operation cost is 7 dollars/time, and the electricity price is 0.7 dollars /kWh.

According to the time division method proposed in this paper, the VFD of each time point of the system is obtained as shown in Figure 3. It can be seen that the E(t) at 9 o'clock and 22 o'clock are much larger than others, so select these two points as the starting point of reconfiguration and divide time division into 3 parts: 1 to 8, 9 to 21, 22 to 24.

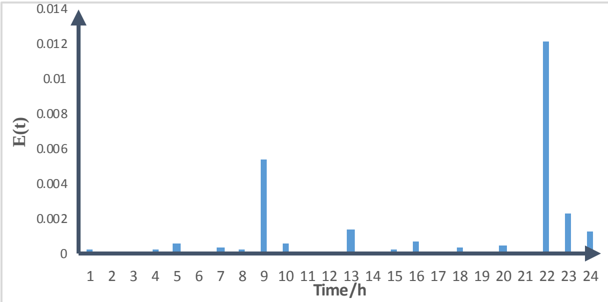

Fig 3 Voltage distance index values at different times in traditional passive scenarios

According to the results of time division, the reconfiguration scheme is compared with the reconfiguration schemes of the Reference [2] and [3]. It can be seen that the scheme is sufficient to adapt to the traditional distribution network. For convenience, abbreviate "disconnect" as "DT" in the next tables.

Tab 4 Comparison of reconfiguration schemes

Scheme of Reconfiguration	Switch operation scheme	Active power loss(kWh)/switching operation times /operating costs(dollars)
Initial structure	DT 8-21，9-15，12-22，18-33，25-29	1471/0/1029.7
Ref. [2]	0：00：DT7-8，9-10，14-15，18-33，25-29 8：00：DT 7-8，9-10，14-15，32-33，25-29 21：00：No operation	1049/8/790.65
Ref. [3]	0：00：DT 6-7，9-10，13-14，9-15，25-29 8：00：No operation 21：00：No operation	1238/6/908.6
This paper	0：00：DT 7-8，9-10，14-15，32-33，25-29 8：00：No operation 21：00：No operation	1049/8/790.3

4.4 Dynamic reconfiguration of distribution network with distributed wind power access scene

The modified IEEE 33 bus distribution system is used for analysis. Distributed wind turbines with rated capacity of 700 kW are connected at node 8 and 18, and the power factor of wind turbines is 0.95.

Similar to section 4.3, we can get Figure 5. Select 10 o'clock ,16 o'clock and 23 o'clock as the starting point of reconfiguration and divide time division into 4 parts: 1to 9, 10 to 15, 16 to 22,23 to 24.

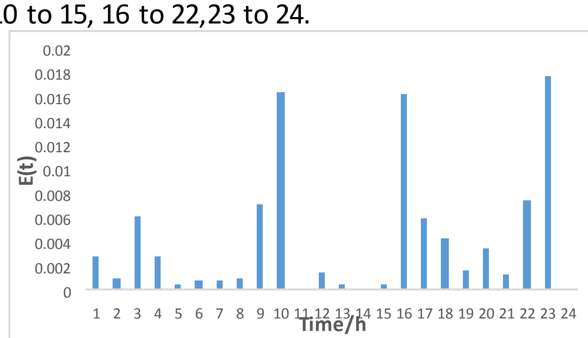

Fig 5 Voltage distance index values at different times integrating distributed wind powers

In this section, considering the error of distributed wind power output prediction value, we use Latin hypercube sampling method to generate wind power scene samples and reduce them [8] to get the final scenario. In order to ensure the safe operation of distribution network, the results of reconfiguration must satisfy the static security constraints of distribution network operation in all scenarios. The results are compared with those in [9] as shown in Table 5.

Tab 5 Comparison of reconfiguration schemes with wind power

Scheme of reconfiguration	Reconfiguration time	Switch operation scheme	Active power loss(kWh)/switching operation times /operating costs(dollars)
Initial structure	----------	DT 8-21，9-15，12-22，18-33，25-29	---------------
Scheme that does not consider uncertainty	0：00	DT 6-7，13-14，9-15，12-22，25-29	708/6/537.6
	9：00	DT 6-7，13-14，17-18，12-22，25-29	
	15：00	DT 6-7，13-14，17-18，12-22，25-29	
	22：00	DT 6-7，13-14，17-18，12-22，25-29	
Scheme that considers uncertainty	0：00	DT 8-9，9-10，31-32，8-21，25-29	807/12/648.9
	9：00	DT 8-9，9-10，31-32，8-21，25-29	
	15：00	DT 6-7，8-9，9-10，18-33，25-29	
	22：00	DT 6-7，8-9，9-10，15-16，25-29	
Scheme in Ref. [9]	0：00	DT 6-7，13-14，17-18，12-22，25-29	712/6/540.4
	11：00	DT 6-7，13-14，17-18，12-22，25-29	
	13：00	DT 6-7，13-14，17-18，12-22，25-29	
	14：00	DT 6-7，13-14，17-18，12-22，25-29	
	15：00	DT 6-7，13-14，17-18，12-22，25-29	
	18：00	DT 6-7，13-14，17-18，12-22，25-29	
	19：00	DT 6-7，13-14，17-18，12-22，25-29	

In this paper, the whole period is divided into four time periods, which, compared with the seven time periods divided by the literature [9], can greatly reduce the subsequent reconfiguration operation. In addition, it can be seen from the comparison of reconfiguration results that the scheme of this paper is superior to the scheme of [9] when the uncertainty of wind power output is not considered. At the same time, the scheme of considering the wind power output uncertainty is given. To prove the robust applicability of the scheme, the three schemes in Table 5 are simulated in the random scenario described in Table 6, and the comparison of voltage standard values at node 32 is given in Figure 6.

Tab 6 Information of random scene

Time/h	1	2	3	4	5	6
Wind power/kW	288	373	174	62	105	181
Time/h	7	8	9	10	11	12

Wind power/kW	159	40	94	0	0	78
Time/h	13	14	15	16	17	18
Wind power/kW	0	45	95	0	145	279
Time/h	19	20	21	22	23	24
Wind power/kW	81	395	294	235	345	368

From Figure 6, it can be seen that the reconfiguration scheme that considers the uncertainty of wind power output can ensure that the node voltage of the distribution network does not exceed the limit under the random scenario, while the other two schemes have exceeded the lowest limit at 16:00, which does not meet the requirements of safe operation of the distribution network.

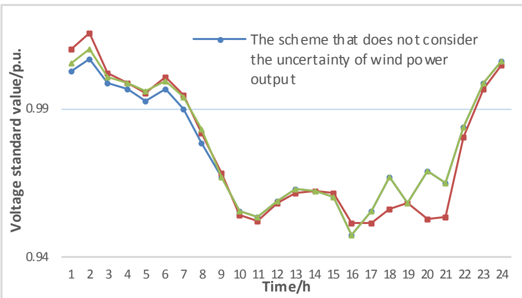

Fig 6 Voltage value of node 32 in each scheme under random scenario

5. CONCLUSION

Aiming at the dynamic reconfiguration of distribution network with distributed wind power, this paper proposes a dynamic reconfiguration method for robust and safe operation of distribution network, considering switching operation constraints and voltage fluctuation deviation. The application of the method proposed in this paper is beneficial to the large-scale access of wind energy to the power system. The main work includes:

1) Propose the voltage fluctuation deviation of distribution network nodes which can reflect the development trend of the whole state of distribution network. According to the distribution of the voltage fluctuation deviation value, the reconfiguration time division result can be obtained intuitively. The method is simple and easy to operate.

2) Considering the rule that the distribution network switch does not allow continuous operation in a short period of time, construct a single switch operation cost model and introduce it into the distribution network dynamic reconfiguration model to limit the continuous actions of the switch in a short period of time.

3) An improved binary particle swarm optimization algorithm for dynamic reconfiguration of distribution network is proposed. The improved algorithm has strong global optimization ability and can improve search efficiency.

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