A Novel Reconfiguration Strategy of Distribution Network

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Abstract. Distribution network reconstruction is important for the reliable operation of distribution network. This paper establishes a mathematical model by using random weight for multi-objective optimization. A new algorithm is proposed based on binary particle swarm optimization (BPSO) algorithm, which can quickly adjust topology and cut off load in limit state. The new algorithm improves the distribution network's reliability with the advantages of lowest power loss, better load balance and highest power supply capacity. Finally, the performance of the proposed method is tested on IEEE 33-node power distribution system.

1. Introduction

Distribution network reconstruction is a self-healing control method that can realize optimal operation of distribution network [1]. It changes the topology of the network by adjusting the combination of tie switches and sectional switches. In recent years, with the expansion of power grid and increase of distributed generation (DG), reconstruction technology has become an important guarantee for the safe, economical and stable operation of the distribution network. The researches of reconstruction focus on improving power supply capacity, reducing power losses, and improving load balance [2, 3, 4].

Distribution network reconstruction is a multi-constrained and multi-objective optimization problem. Experts and scholars at home and abroad had conducted a lot of research on optimization algorithms. Paper [5] used the ring network coding of the contact switch to determine the network connectivity. Paper [6] analyzed and researched the mathematical model of DG power flow calculation based on the forward and backward method. Paper [7] proposed a new algorithm based on BPSO and tabu search algorithm which needn’t to judge the radiation structure of the network. Paper [8] proposed a hierarchical distributed optimization algorithm to reduce the dimensions. Paper [9] proposed an adaptive cross-rate and mutation rate genetic algorithm to overcome local convergence.

The distribution network reconstruction includes two situations: optimization before system fails and recovery after failure. This paper analyzes and studies the former case, and establishes a reconstruction model that can dynamically adjust reconstruction scheme according to operating status. In order to overcome the problems of slow convergence and local convergence, a novel algorithm is proposed. This algorithm can quickly adjust the topology and cut off the load under extreme condition. The characteristics of low loss, high power supply capacity and fast reconstruction speed significantly improve the stability of the system in high-risk state.
2. Mathematical model of distribution network reconstruction

2.1. The objective function

The objectives of the distribution network reconstruction contain low power loss, high load balance, fewer operations and high power supply capacity [10]. In the reconstruction problem, this paper normalizes the above four indicators to achieve the goal of multi-objective optimization. The objective function is shown below.

\[ \min F = \omega_1 f_1 + \omega_2 f_2 + \omega_3 f_3 + \omega_4 f_4 \]

\[ \begin{align*}
\min f_1 &= \sum_{i=1}^{n} \frac{P_i^2 + Q_i^2}{U_i^2} s_i f_i \\
\min f_2 &= \max_{i \in B} \left( \frac{I_i}{I_{Ni}} \right) - \min_{i \in B} \left( \frac{I_i}{I_{Ni}} \right) \\
\min f_3 &= \sum_{i=1}^{N} |x_i - x_{i0}| \\
\max f_4 &= - \left( \sum_{i=1}^{n} S_i + \sum_{j \in D} mS_j \right)
\end{align*} \]  

(1)

Where, \( f_1 \) is objective function of power loss [11], \( n \) is the total number of lines in the network; \( i \) is the label of line; \( U_i \) represents node voltage at the end of the line; \( P_i \) and \( Q_i \) respectively represent active and reactive power flowing through the line; \( s \) indicates the status of line (\( s_i = 0 \), means line \( i \) is disconnected; \( s_i = 1 \), means line \( i \) is closed); \( r \) is the equivalent resistance of the line. \( f_2 \) is objective function of load balance, \( I_i \) represents actual load of branch \( i \); \( I_{Ni} \) is the rated capacity of branch \( i \). \( f_3 \) is objective function of the number of operations [12]. \( N \) is the total number of switches, \( x_{i0} \) and \( x_i \) represent the states before and after reconfiguration of switch \( i \), respectively. \( f_4 \) is the minimal expression form of the maximum power supply capacity.

2.2. The restrictions

When solving the objective function, the following constraints must be met [13].

\[ \begin{align*}
P_{G_i} + P_i &= P_{Li} + V_i \sum_{j=1}^{Nb} V_j \left( G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij} \right) \\
Q_{G_i} + Q_i &= Q_{Li} + V_i \sum_{j=1}^{Nb} V_j \left( G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij} \right)
\end{align*} \]  

(2)

Where, \( P_{G_i} \) and \( Q_{G_i} \) respectively represent the active and reactive power injected by DG to node \( i \); \( P_i \) and \( Q_i \) respectively represent the active and reactive power injected to node \( i \); \( P_{Li} \) and \( Q_{Li} \) represent the load; \( V_i \) is the voltage amplitude of node \( i \); \( G_{ij} \), \( B_{ij} \), \( \delta_{ij} \) respectively represent the conductance, susceptance, and voltage phase difference between nodes \( i \) and \( j \).  

\[ \begin{align*}
V_{i_{\text{min}}} &\leq V_i \leq V_{i_{\text{max}}} \\
I_i &\leq I_{i_{\text{max}}} \\
S_{G_{\text{min}}} &\leq S_G \leq S_{G_{\text{max}}}
\end{align*} \]  

(4)

The first term of the above formula is the voltage constraint of node \( i \), \( V_{i_{\text{min}}} \) and \( V_{i_{\text{max}}} \) respectively represent the maximum and minimum values of the voltage. The second term is the
constraint of line capacity, $I_i$ and $I_{i,max}$ respectively represent the current of the branch $i$ and the maximum current allowed to flow. The third item indicates the output limit of DG.

3. **Select the model of reconstruction**

When the distribution network is in different operating states, its risk level is different, so the goals of reconstruction will also be different. The relationship between reconstruction objectives and risk levels is shown in Figure 1. And the reconstruction schemes of the system in different operating states are shown in Figure 2.

**Figure 1.** Reconstruction objectives.

**Figure 2.** Reconstruction schemes.

When constructing objective function, the paper uses random weight to comprehensively consider four indicators. The weighting coefficients in different operating conditions are shown in Table 1.

**Table 1.** The weighting coefficients.

| operating status  | $\omega_1$ | $\omega_2$ | $\omega_3$ | $\omega_4$ |
|-------------------|------------|------------|------------|------------|
| normal state      | 0.65       | 0.15       | 0.08       | 0.12       |
| abnormal state    | 0.5        | 0.25       | 0.15       | 0.1        |
| alert state       | 0.08       | 0.45       | 0.08       | 0.39       |

4. **Improved BPSO algorithm**

4.1. **Traditional BPSO algorithm**

BPSO algorithm is the application of particle swarm algorithm in discrete problems. The BPSO algorithm uses the binary variable "0-1" to represent the particle's position information. The particle's velocity is used to indicate the probability of the particle's position being "1", and the probability of the particle's position is "1" is proportional to the velocity [14, 15, 16]. The iterative process of speed and position in the BPSO algorithm is as follows.

$$O_{im}^{k+1} = \alpha O_{im}^k + a_1 r_1 (p_{im}^k - X_{im}^k) + a_2 r_2 (g_{m}^k - X_{im}^k)$$

$$S(X_{im}^k) = 1/1 + e^{-O_{im}^{k+1}}$$

$$X_{im}^{k+1} = 1 \quad \text{rand} < \text{Sig}(X_{im}^{k+1})$$

$$X_{im}^{k+1} = 0 \quad \text{rand} > \text{Sig}(X_{im}^{k+1})$$

Where, $k$ is the number of iterations; $O_{im}^k$ and $X_{im}^k$ respectively represent velocity information and position information of the $i$-th particle in the m-dimensional space; $p_{im}^k$ and $g_{m}^k$ respectively
represent individual optimal value and global optimal value; $r_1$ and $r_2$ are random numbers between $[0,1]$; $a_1$ and $a_2$ are acceleration coefficients. In order to prevent local convergence due to function saturation during the iteration process, the speed is limited to (-5, 5).

4.2. Improved BPSO algorithm

The BPSO algorithm usually needs long computational time and its result is not excellent when the system is in a high-risk state. Therefore, we proposed an improved BPSO algorithm, which can quickly adjust the system topology and cut off the load in the limit state.

4.2.1. Fast topology adjustment. When the system is in a high-risk state, the stability of the system can be improved by adjusting topology rapidly. The idea is to transfer high-risk equipment to the end of the power supply path and transfer the downstream load of the original high-risk equipment to other lines. The steps are as follows.

(1) Find the power supply path where high-risk device is located and by using the Floyd algorithm and its downstream load.

(2) If the high-risk device is upstream of the power supply path, it can be transferred to the end of the path or directly withdrawn by controlling tie switches and sectional switches.

(3) The downstream load of the original high-risk equipment is transferred to a path with large remaining capacity or directly withdrawn from operation.

Take the 14-node network shown in Figure 3 as an example to briefly explain the adjustment process. The G node in Figure 3 represents the power source, and the remaining nodes represent loads. Figure 3 (a) is the topology before reconfiguration, and the other two are the topologies after reconstruction. Assuming that the device of node $j$ is in a high-risk state, the reconstruction strategy when the system is in an abnormal state and a fragile state were discussed separately.

![Figure 3. Topology of distribution network](image)

(a) When the device of node $j_1$ is in abnormal state, the device of node $j_2$ is out of operation, and the device of node $j_3$ (or $j_4$) is put into operation. Transfer the device of $j_1$ to the end of the path and the downstream load powered by $j_1$ to node $j_3$ (or $j_4$). The result is shown in Figure 3 (b).

(b) When the device of node $j_1$ is in alert state, the device of node $j_1$ needs to be taken out of operation. Put the device of node $j_3$ (or $j_4$) into operation so that the load of the node is powered by $G_1$ (or $G_3$) through node $j_3$ (or $j_4$). The result is shown in Figure 3 (c).

4.2.2. Load-shedding strategy. When the system is in a fragile state or the power cannot be restored globally after a system failure, part of the load needs to be cut off to maintain the stability of the system. The steps of load shedding strategy are as follows.

(1) Perform a risk assessment of the system to find overloaded lines and nodes with voltage overruns in the current state.
(2) Find the power supply paths for overload lines and loads with voltage quality problems.
(3) Evaluate the priority of the loads on the paths. Starting from the end of the paths, the loads are removed one by one according to the order of load level, controllability, and capacity.
(4) If load in the end of the line is more important, do not remove it and remove the tertiary load located upstream of it.
(5) Check whether the electrical quantity meets the constraints when removing a load, then proceed to the next step.

5. Example analysis

This paper uses IEEE 33-node power distribution system [17], which has 33 nodes, 37 branches and four DGs, to verify the new algorithm, as shown in Figure 4. The reference voltage is 12.66kV and total load is 5084.26 + j2547.32kVA. The location and capacity of each DG are shown in Table 2.

Assuming that the system is running in normal state, the new algorithm and two existing algorithms are used to reconstruct the distribution network. The simulation results are shown in Table 2.

Table 2. The locations and capacities of DGs.

| Number(DG) | node | Capacity(kW) | Power factor |
|------------|------|--------------|--------------|
| 1          | 13   | 400          | 0.9          |
| 2          | 17   | 250          | 0.8          |
| 3          | 25   | 450          | 0.95         |
| 4          | 30   | 400          | 1            |

Table 3. Simulation results.

| Scheme                | Open switches | Loss(kW) | Load balance | Number of operations | Power supply capacity |
|-----------------------|---------------|----------|--------------|----------------------|-----------------------|
| Traditional BPSO      | 33,35,36,37   | 0.1211   | 0.2501       | 2                    | 1.697                 |
| Paper[7]              | 6,8,13,32,37  | 0.1019   | 0.2398       | 8                    | 1.4305                |
| Paper[8]              | 7,9,14,32,37  | 0.0875   | 0.2476       | 8                    | 1.8593                |
| Method of this paper  | 6,9,14,31,37  | 0.0850   | 0.2496       | 8                    | 2.1405                |

Traditional BPSO algorithm has the least number of switching operations, but the power loss is large and the power supply capacity is not high. The other three methods have the same number of switching operations. Although the method proposed in reference [7] reduces the power loss, the power supply capacity is also reduced. The method of reference [8] greatly reduces the loss, but the power supply capacity is not high. The algorithm proposed in our paper has the advantages of minimum power loss, highest power supply capacity and better load balance. The results prove the superiority of the algorithm proposed in this paper.
6. Conclusion

This paper establishes a mathematical model for distribution network reconstruction by using a method of random weight. Then, a novel algorithm is proposed based on the BPSO algorithm. The novel algorithm can adjust the topology quickly and remove the load when the system is in the limit state. The new method has the characteristics of small power loss, high power supply capacity, and lowest computational time, which significantly improves the stability of the distribution network in a high-risk state. Finally, the IEEE 33-node system was used for simulation, which verified the correctness and effectiveness of the novel algorithm.

References

[1] Taleski R, Rajicic D. Distribution network reconfiguration for energy loss reduction[J]. IEEE Transactions on Power Systems, 1997, 12(1):398-406.

[2] Hongjian W, Xia L, Bin L, et al. Membrane Computing Based Genetic Algorithm for Dynamic Reconfiguration of Distribution Network with Dividing Time and Considering Electric Vehicles and Wind Turbines[J]. Transactions of China Electrotechnical Society, 2016.

[3] Yitao Hu, Ning Hua, Chun Wang, Jiaolong Gong and Xiangshuo Li, "Research on distribution network reconfiguration," 2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering, Changchun, 2010, pp. 176-180.

[4] G.R. Mettam, How to prepare an electronic version of your article, in: B.S. Jones, R.Z. Smith (Eds.), Introduction to the Electronic Age, E-Publishing Inc., New York, 1999, pp. 281-304.

[5] MA Xiufan, DING Ning, LI Long. Judging radial and connectivity of network in distribution networks reconfiguration [J]. Transactions of China Electrotechnical Society, 2014, 29(8): 289-293.

[6] Zhang L, Tang W. Back/forward sweep power flow calculation method of distribution networks with DGs[J]. Diangong Jishu Xuebao/Transactions of China Electrotechnical Society, 2010, 25(8):123-130.

[7] L. Deng, J. Fei, C. Ban, C. Cai and X. Zhang, "The simulation of self-healing restoration control for smart distribution network," 2015 6th IEEE International Conference on Software Engineering and Service Science (ICSESS), Beijing, 2015, pp. 482-485.

[8] Wang C X, Guo S H, Li C H, et al. Application of Genetic Algorithm Based on Gene Therapy Theory for Distribution Network Reconfiguration[C]// 2008.

[9] S. Nematshahi and H. R. Mashhadi, "Distribution network reconfiguration with the application of DLMP using genetic algorithm," 2017 IEEE Electrical Power and Energy Conference (EPEC), Saskatoon, SK, 2017, pp. 1-5.

[10] J. Yu, F. Zhang and J. Dong, "Distribution network reconfiguration based on minimum cost of power supply," 2009 International Conference on Sustainable Power Generation and Supply, Nanjing, 2009, pp. 1-4.

[11] Zheng Ruiguan, Zhang Zhiya, Wang Haiming and Liu Feng, "Economical research of distribution network reconstruction in emigration areas," 2011 IEEE Power Engineering and Automation Conference, Wuhan, 2011, pp. 67-70.

[12] Y. Yan et al., "Load Balancing Distribution Network Reconfiguration Based on Constraint Satisfaction Problem Model," 2018 China International Conference on Electricity Distribution (CICED), Tianjin, 2018, pp. 2515-2519.

[13] R. Hasanpour, B. M. Kalesar, J. B. Noshahr and P. Farhadi, "Reconfiguration of smart distribution network considering variation of load and local renewable generation," 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Milan, 2017, pp. 1-5.

[14] Kennedy J, Eberhart R C. A discrete binary version of the particle swarm algorithm[C]// 1997 IEEE International Conference on Systems, Man, and Cybernetics. Computational Cybernetics and Simulation. IEEE, 1997.

[15] Xu Yichun, Xioa Renbin. An improved binary particle swarm optimizer[J]. Pattern Recognition and Artificial Intelligence, 2007, 20(6): 788-793.
[16] Shi Y. A Modified Particle Swarm Optimizer[C]// Proc. of IEEE ICEC conference, Anchorage. 1998.

[17] Song Y H, Wang G S, Johns A T, et al. Distribution network reconfiguration for loss reduction using fuzzy controlled evolutionary programming[J]. IEE Proceedings-Generation, Transmission and Distribution, 1997, 144(4):345-0.