

## The Optimization Study about Fault Self-Healing Restoration of Power Distribution Network Based on Multi-Agent Technology

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**Abstract:** In order to quickly and accurately locate the fault location of the distribution network and increase the stability of the distribution network, a fault recovery method based on multi-objective optimization algorithm is proposed. The optimization of the power distribution network fault system based on multiagent technology realizes fast recovery of multi-objective fault, solve the problem of network learning and parameter adjustment in the later stage of particle swarm optimization algorithm falling into the local extreme value dilemma, and realize the multi-dimensional nonlinear optimization of the main grid and the auxiliary grid. The system proposed in this study takes power distribution network as the goal, applies fuzzy probability algorithm, simplifies the calculation process, avoids local extreme value, and finally realizes the energy balance between each power grid. Simulation results show that the Multi-Agent Technology enjoys priority in restoring important load, shortening the recovery time of power grid balance, and reducing the overall line loss rate of power grid. Therefore, the power grid fault self-healing system can improve the safety and stability of the important power grid, and reduce the economic loss rate of the whole power grid.

**Keywords:** Multi agent, technology, power distribution network, fault self-healing.

### 1 Introduction

The intelligent electrification development in modern society has made the distribution network more and more complex, and it brings such problems as the failure rate of damage, overheating and rises in a straight line. In this context, scholars at home and abroad have introduced a variety of optimization algorithms to tackle the aforesaid problems, so as to facilitate their efforts to realize distribution network fault recovery [Chen, Liu and Chen (2015)]. Some scholars put forward the tree structure theory, hoping to layer the distribution network fault, reduce the “dimension” of the distribution network, and quickly locate the fault [Feng, Ping and Wan (2019)]. However, such a method involves a large amount of calculation, and it is easy to generate local extreme value. Compared with other algorithms, the tree structure has fatal shortcomings, namely, the

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calculation operation is too complex. Therefore, the active load optimization algorithm based on the active load is proposed, which not only greatly simplifies the analysis process, but also reduces the “dimension” of the whole operation. This topology model adopts binary particle swarm optimization algorithm. Although it improves the speed of fault diagnosis, there are still limitations of local extremum. Therefore, it is necessary to integrate fuzzy genetic algorithm to effectively control the bad rate and mutation rate in the distribution network, and utilize fuzzy processing to avoid local convergence. First of all, the objective function should be determined, then each index should be analyzed by AHP, and the corresponding weight value should be given, which can not only realize the optimization of binary particle swarm, but also further limit the immature convergence problem [Hu, Guo and Lan (2015)]. Therefore, based on all of the above analysis, we constructed a multi-agent system composed of the whole system control coordination agent, the network control agent, the distributed power agent, and the bus agent, and carried out the fault analysis of the particle swarm Bayesian network method. Fortunately, the particle swarm optimization reduces the “dimension” of Power Distribution Network, and Bayesian method effectively avoids local extreme value [Jiang, Xing and Pang (2018)]. The combination of the two greatly improves the speed and accuracy of fault diagnosis, and provides reasonable recovery strategies for dispatchers, thus making up for the shortcomings of different algorithms [Liu and Wang (2018)].

## 2 Optimization objectives and constraints

### 2.1 Objective functions

Once the power grid fails, it is necessary to take reducing the power loss as the goal to restore the power grid step by step, otherwise it will have a serious impact on the whole power grid [Liu, Zhang and Shu (2015)]. First of all, give priority to restoring important loads; secondly, recover power loss load as much as possible; thirdly, maximize the balance degree of power grid; finally, minimize the line loss of power grid. The relevant calculation formula is as follows:

(1) Recovery of important load loss

$$\max f_1(x) = \sum_{i=1}^C (1-A_i)L_i \quad (1)$$

The recovery of important load loss is the premise of all steps as well as the primary recovery index of fault self-healing system, which plays an incomparable role in fault healing [Liu and Li (2015)]. As shown in Eq. (1),  $C$  is the set of important load nodes;  $L_i$  is the load of node  $i$ ;  $A_i$  is the state of node  $i$ ; 0 refers to the power living state, 1 refers to the power failure state.

(2) Power loss load recovery

$$\max f_2(x) = \sum_{i=1}^M \beta_i L_i \quad (2)$$

To judge the loss of power load recovery, it is necessary to judge each agent node and the main distribution power supply, and calculate the load balance between different representatives [Li, Zhang and He (2015)]. As shown in Eq. (2),  $M$  is the set of the

non-fault nodes area;  $\beta_i$  is the state of node  $i$ ; 0 refers to Power living state, 1 refers to Power failure state.

(3) Distribution network equilibrium level

$$\min f_3(x)=E=\sum_{j=1}^{\Omega} \left( H_i - \frac{\sum_{k=1}^{\Omega} H_k}{n} \right)^2 \tag{3}$$

The balance level of the distribution network indicates that the power flow value among the distributed networks is maintained in a balanced state, and the voltage, current and other indicators are restored to the standard range [Mohammadi, Mozafari and Solimani (2013)]. As shown in Eq. (4),  $\Omega$  is the node load in the fault area,  $H_i$  is the line load rate of line  $i$ ;  $H_k$  is the branch  $k$  in the power grid.

Line loss rate of power grid

$$\min f_4(x)=\sum_{i=1}^N I_i^2 R_i \tag{4}$$

The line loss rate of power grid is the premise index of fault self-healing, which represents the self-healing situation of power grid. As shown in Eq. (4),  $N$  is the collection of line branches;  $I_i$  and  $R_i$  are the current and resistance of grid  $i$ ; 0 indicates the charged state and 1 indicates the power off state.

All the operation in the Power Distribution Network, which is the comprehensive level of power flow operation, reflects the equilibrium level and has the overall characteristics. The smaller the value of  $E$  at the same load, the more average the line power flow and the higher the stability of the power grid [Sun, Wu and Shang (2017)]. Compared with the common system safety operation indexes, the operation balance degree of the distribution network, which has the overall characteristics, is likely to reflect the comprehensive level [Soroudi, Siano and Keane (2015)].

**2.2 Optimization objectives**

It is assumed that  $RE$  represents the factor of the proportion in normal operation power grid [Tan, Lv and Li (2013)]. The higher the value, the lower the failure rate in Power Distribution Network. The expression is shown in Eq. (5).

$$RE = \begin{cases} \left( 1 - \frac{\sum P_{f_1} + \sum P_{f_2}}{\sum P_{f_3} + \sum P_{f_4}} \right) \times 100\% & RE_1 \\ \left( \frac{\sum P_{f_3} + \sum P_{f_4}}{\sum P_{f_1} + \sum P_{f_2}} \right) \times 100\% & RE_2 \end{cases} \tag{5}$$

In which,  $RE1$  is the total output of  $f_1$  and  $f_2$ , which is less than the total output of  $f_3$  and  $f_4$ ;  $RE2$  is the total output of  $f_1$  and  $f_2$ , which is more than the total output of

$f_3$  and  $f_4$ . Notably, the Eq. (5) shows that the proportion of sub power grid is large and the failure rate of the Power Distribution Network is low in the condition of *RE1*; at same time, the proportion of sub power grid is small and the failure rate of Power Distribution Network is high in the condition of *RE2*.

### 2.3 Fault analysis

When the Power Distribution Network is connected to the grid, the control of network control agent, distribution agent and coordination agent should be fully considered. Assume that the total failure rate is  $F_{totle}$ , the control fault of power distribution network is  $F_{Power}$  distribution network, the distributed fault is  $F_{distribution}$ , the coordinated fault is  $F_{coordinate}$ , and the fault repair is  $F_{repair}$ . The expression is as shown in Eq. (6) as below:

$$F_{totle} = F_{updatei} + \int_0^t \sum_{i=1}^n F_{gridi} i P_i(t) dt + \int_0^t \sum_{i=1}^n F_{distribution} i P_i(t) dt + \int_0^t \sum_{i=1}^n F_{coordinatei} P_i(t) dt + \int_0^t \sum_{i=1}^n (F_{repairi} P_i(t+D) - F_{repairi} P_i(t)) dt \quad (6)$$

The fault rate is mainly the sum of the unit grid fault  $F_{per}$  in the Power Distribution Network, which is as shown in Eq. (7).

$$F_{per} = \frac{i_{failure\ rate} (1 + i_{failure\ rate})^{Tn} F_{totle}}{(1 + i_{failure\ rate})^{Tn} - 1 \sum_{h=1}^{h=8760} P_{load}(h)} \quad (7)$$

In Eq. (7),  $i_{failure\ rate}$  is the risk rate during operation; TN is the service cycle of the Power Distribution Network system. Notably, the unit with the shortest service cycle is the main one;  $P_{load}$  is the failure risk of the system load in unit time.

### 2.4 Optimization objective function

In order to calculate the minimum failure rate and the minimum failure maintenance, the parameters stated above can be set as the main parameters, and the objective function  $G$  can be constructed, which is as shown in Eq. (8):

$$\min G(RE | F_{per}) \quad (8)$$

## 3 Intelligent communication early warning vulnerability detection algorithm

### 3.1 Internet of things technology

To determine if self-healing system is effective, we need to carry out vulnerability detection [Wang and Zhou (2017)]. Multi-agent technology, based on the conditional probability in each node, is to utilize prior knowledge to each  $X_i$ . Meanwhile, constraint association nodes among  $(X_1 \cdots X_n)$  is analyzed. Among all these operations, the parent node is the key, and is the focus of the Multi-agent technology [Xu, Li and Lin (2014)]. Therefore, the joint probability distribution of this technology is shown in Eq. (9):

$$P(X_1, \dots, X_n) = \prod_{i=1}^n P(X_i | P_f(X_i)) \tag{9}$$

First, a set of training data is given, and then the network topology is realized by array structure learning [Xu and Xu (2018)]. In the light of the corresponding standard values, the parameters of the network topology are evaluated. The specific network topology process is shown in Eq. (10) [You, Liu and Yu (2012)]:

$$BIC(BN|D) = \sum_{i=1}^n \sum_{k=1}^{r_i} \sum_{j=1}^{q_i} N_{ijk} \ln \frac{N_{ijk}}{N_{ij}} - N \left| \sum_{i=1}^n q_i (r_i - 1) \right| \tag{10}$$

As shown in Eq. (10), D is the sample data set after standardization; N is the sample quantity after standardization; n is the sample quantity after standardization;  $N_{ij}$  is the sample quantity when the value of the i parent node is j;  $N_{ijk}$  is the sample quantity when the value of the i node is k and the value of the parent node is j;  $q_i$  represents the value of the i variable;  $r_i$  is the combination value from the parent node of the i variable; at the same time, the Akaike information judgment criterion is utilized to adjust the related items of the setting model, so as to realize data standardization and improve the fitting accuracy of the model [You, Liu and Zhong (2014)].

$$f(n) = \sum_{i=1}^n -\ln \left( \frac{n}{i} \right)^{i+1} 2^{i(n-i)} f(n-1) \tag{11}$$

Although the above algorithm obtains the key fault indicators of the power grid, the number of nodes in the fault grid is huge, which makes the processing time of multi-agent technology prolonged, so it is necessary to optimize its calculation process and enhance the efficiency of the algorithm [Yang, Lv and Li (2015)].

### 3.2 Early warning vulnerability detection algorithms

In the early stage of fault self-healing, the steps of node selection, inter network coordination, and iterative optimization of subnet are taken to obtain the global optimal spatial particles. The calculation formula is shown in Eq. (12) [Zhu and Liu (2017)].

$$\begin{cases} X_i(t) = X_i(t-1) + V_i(t) \\ V_i(t) = w \bullet V_i(t-1) + c_1 r_1 (P_{gi}(t-1) - X_i(t-1)) + c_2 r_2 (P_g(t-1) - X_i(t-1)) \end{cases} \tag{12}$$

$X_i$  is the position and speed of the ith particle in the particle space;  $V_i$  is the optimal position of the ith particle in the calculation space;  $P_{gi}$  represents the optimal position in the calculation space [Zhong, Yu and Sun (2014)];  $w$  is the inertia weight in particle operation;  $c_1$  and  $c_2$  are the acceleration adjustment confidents in particle operation;  $r_1$  and  $r_2$  are the random adjustment number in the calculation space [0,1]; t is the early warning vulnerability detection calculation. Though the above operations reduce the complexity of calculation, it is likely to have local optimal problems and bring about multi valued calculation results in the process of calculation [Zhang, Yang and Zeng (2015)].

### 3.3 Intelligent communication early warning vulnerability detection algorithms

The main limiting method of local extreme value is to set the threshold value. Once the extreme value is higher or lower than the threshold value, it is necessary to judge the extreme value to reduce the occurrence rate of the local extreme value [Zhang, Zeng and Zhang (2014)]. We utilize the advantages of Bayesian network learning and genetic algorithms, set the limit threshold, and carry out iterative learning for multi-agent nodes to build the optimal calculation model. The calculation process is shown in Eq. (13) [Zhang and Cai (2018)]:

$$f_1(X_i(t-1), w) = \begin{cases} M(X_i(t-1)), & w > r_1 \\ X_i(t-1), & w < r_1 \end{cases}$$

$$f_2(f_{1put}, c_1) = \begin{cases} C(f_{1put}), & c_1 > r_2 \\ f_{1put}, & c_1 < r_2 \end{cases} \quad (13)$$

$$f_3(f_{2put}, c_1) = \begin{cases} C(f_{2put}), & c_2 > r_3 \\ f_{2put}, & c_2 < r_3 \end{cases}$$

In which,  $r_3$  is the random number in the  $[0, 1]$  interval;  $f_{1put}$  and  $f_{2put}$  are the output results;  $M$  and  $C$  are two operations of the early fault self-healing algorithm, namely, mutation operation and cross operation. In the iterative calculation of the particle velocity and position, the edge particles that do not meet the constraints should be eliminated continuously, and the particle insertion should be carried out according to the relevant parameters of multi-agent technology to ensure the total number of samples is constant [Zhang, Zhang and Liu (2018)]. As shown in Eq. (13), the inertia weight  $w$  determines the search ability of particles. Specifically, the larger the  $w$  value, the stronger the global search ability of the algorithm, and the slower the convergence speed [Zeng, Liu and Zhang (2013)]; the smaller the  $w$  value, the weaker the global search ability, the stronger the local search ability and the faster the convergence speed. The calculation of  $w$  as shown in Eq. (14):

$$w = \frac{w_1(ev_{\max} - ev) + w_n \bullet ev}{ev_{\max}} \quad (14)$$

In which,  $w_1$  is the initial weight and final weight respectively,  $w_n$  and  $ev$ ,  $ev_{\max}$  are the current number of iterations and the maximum number of iterations respectively [Zhong, Yu and You (2015)]. As shown in Eqs. (14) and (15), the calculation result of particle acceleration coefficient belongs to linear variable. By setting a certain threshold value, the optimized algorithm can avoid local extreme value, so as to ensure that the final calculation result is the global optimal convergence extreme value.

$$\begin{cases} c_1 = \frac{c_{11}(e_{\max} - ev) + c_{1n} \bullet ev}{ev_{\max}} \\ c_2 = \frac{c_{21}(e_{\max} - ev) + c_{2n} \bullet ev}{ev_{\max}} \end{cases} \quad (15)$$

As shown in Eq. (15),  $c_{11}$  is the initial acceleration coefficient;  $c_{21}$  is the final acceleration coefficient,  $c_1$  and  $c_{1n}$  are the initial acceleration coefficients;  $c_2$  and  $c_{2n}$

are the final acceleration coefficients, respectively.

#### 4 Simulation verification

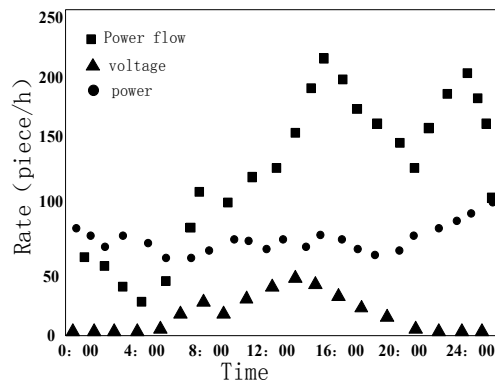
##### 4.1 Basic data

Fourteen nodes in an area power grid are taken as the research object of the fault self-healing system. With the guidance of multi-agent technology, the whole power grid is divided into coordination agent, network control agent, distributed power agent and bus agent. At the same time, the data collected by the above agents is imported into the model, the self-healing situation of power grid fault, the final output result value, the accuracy of the judgment result, and the analysis time of the whole fault are analyzed. The relevant data is shown in Tab. 1.

**Table 1:** The parameters of 14 nodes in an area power grid

Indicators Item	Upper limit of power flow	Lower limit of power flow	Early fault time (h/km)	Later operation and maintenance time (h/km)	Fault judgment cycle (month)	Agent coordination rate (note/min)	The rate of each power grid (note/min)
Control agent	60	0	15000	0.012	30	0	0
Coordination agent	120	0	9000	0.056	15	0	0
Distributed power agent	60	2	6000	0.058	2.8	10	5
Bus agent	60	2	6000	0.052	26	15	5
Related indicators Agency							
Item	Maintenance agent	30	40	90	5	800	0.052
Hierarchical agent	0	0	0	0	17000	0	

The relevant data conform to the actual detection standards, and can be further predicted and simulated. In particular, it should be emphasized that emax meets the node requirements of most power grids. On the basis of the aforementioned parameters, we can get the change chart of the fault self-healing related factors, which is shown in Fig. 1.



**Figure 1:** Variation curve

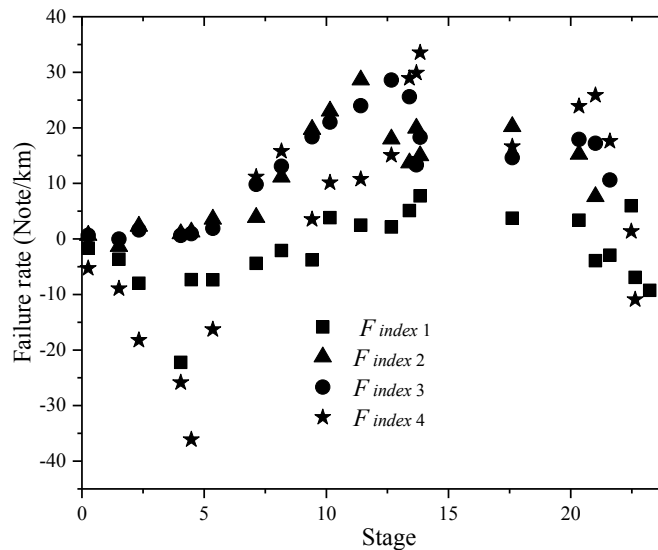
As shown in Fig. 1, the voltage, power flow and power change in fluctuations, but the change amplitude is relatively low, which falls within the fluctuation value range of relevant indexes. To determine the fault measures to be selected, it is necessary to refer to the domestic grid fault standards, and combine the actual operation in the power distribution network, and make multi-agent level by level judgment, as shown in Tab. 2. At the same time, on the basis of referring to the domestic power grid fault standard and in combination with the change of the fault self-healing influence index in Fig. 1, the step-by-step judgment measures are taken, and the specific contents are shown in Tab. 2.

**Table 2:** Power distribution fault and judgment reference

Failure phase	Time	Fault judgment rate standard (note/km)	Actual fault repair rate(note/km)
Peak	am 10:00-pm 16:00 pm 20:00-am 0:00	0.9	0.67
Peacetime	am 06:00-am 10:00 pm 16:00-pm 20:00 am 0:00-am 1:00	0.56	0.48
Underestimate	am 1:00-am 6:00	0.3	0.2

**4.2 Optimization results**

Based on the data in Fig. 1, Tab. 1, MATLAB software is used to simulate and analyze the above parameters, and the optimized index change curve is finally obtained, as shown in Fig. 2.



**Figure 2:** Optimization results of fault self-healing algorithm

As shown in Fig. 2, during 01:00-06:00 am, only control agents can reduce the power grid failure rate. The risk of power grid failure is the lowest. The judgment of bus failure point is relatively accurate. The subordinate grid keeps low power operation and only realizes the self-healing of bus failure. After the fault treatment of the main grid is



completed, the fault point judgment of the subordinate grid is carried out, and the whole sub grid is operated by using the alternative path to maintain the stability; during 06:00-10:00 am, the fault risk is general at this time, and the judgment of the fault point is performed by the auxiliary personnel, so as to realize the operation stability of the whole grid. It is worth noting that during this period, the power grid load is high, and the core is to maintain the stability of power flow. During 10:00 am-16:00 pm, the risk of failure is high and there is a lack of relevant personnel. In order to strengthen the adjustment of distributed sub-grids, the failure points of the main grid and sub-grids are determined at the same time, so as to shorten the recovery time. What needs to be figured out is the maintenance measures and fault judgment are combined to maintain the voltage between different power grids; during 16:00 pm-20:00 pm, the risk of power distribution network fault is medium, and the main fault is still, and then the sub grid fault treatment is carried out. Power companies decide whether to purchase standby line equipment according to the frequency and economic benefits of grid failures. At the same time, the power grid management departments at all levels are on standby for maintenance, and conduct timely troubleshooting according to the actual analysis results of the optimization model. As the data changes in Fig. 2, the multi-agent, based on power grid fault self-healing model, can give better results in different time periods. Based on the overall stability of the power grid, the model can eliminate faults in time and improve the self-healing efficiency.

As shows in above analysis, the maintenance agent in the maintenance system has been adjusted twice within 24 hours, with the depth of each adjustment greater than 80% of the grid failure rate, which is in the lowest guarantee state of grid operation, thus ensuring the stability of grid operation. During 16:00 pm-20:00 pm, although the failure rate is high, the main power grid is the main fault self-healing, and the auxiliary manual detection can maximize the failure time. The simulation results show that the optimal values of RE and Fper are 95.34% and 2.14% respectively, which shows that the fault handling efficiency and loss rate are ideal. As shown in Figs. 2 and 4, the detection of the fault self-healing system is in a high frequency state during the whole stage of high fault rate of the power grid, so as to shorten the fault diagnosis time. At the same time, through the manual fault inspection, we can get better processing effect. During 01:00-06:00, the fault detection frequency of the fault self-healing system is low, but the fault point can still be detected in time to ensure the power supply of the main grid and the stability in the whole grid.

#### ***4.3 Comparison of algorithm optimization degree***

The self-healing system based on multi-agent technology can achieve the expected goal, but the accuracy of fault judgment and self-healing ability still need to be verified. Therefore, MATLAB software is used to compare the optimized algorithm with the traditional algorithm, and to analyze the verification results, as shown in Fig. 3.

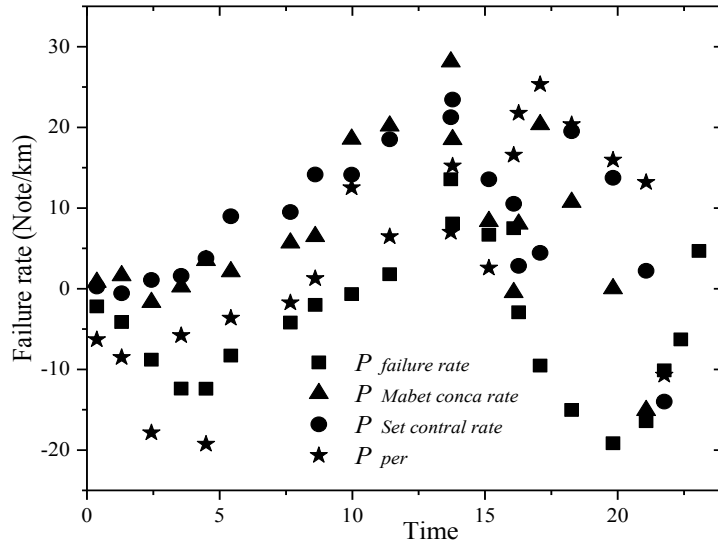


Figure 3: PSO algorithm optimization output results

The fault self-healing algorithm based on multi-agent technology can effectively reduce the fault rate in the distribution network, such as voltage, power and power flow, and accurately judge the fault point through the analysis. At the same time, the fault should be handled in time in combination with the maintenance measures of artificial assistance. Moreover, the optimized algorithm is significantly better than the traditional algorithm in terms of local extreme value control, as shown in Fig. 4.

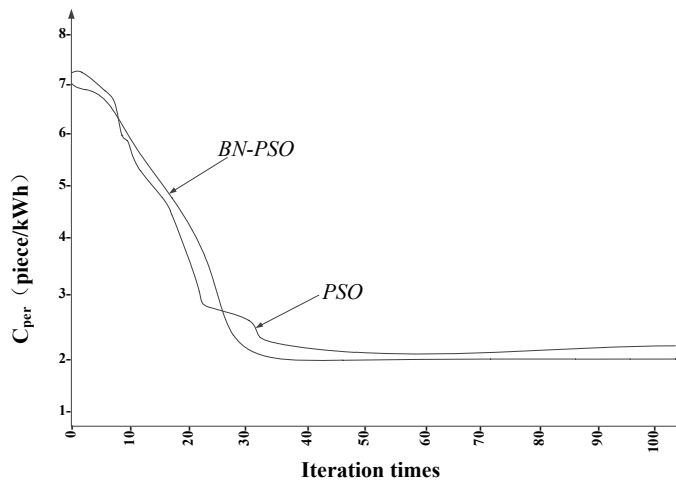


Figure 4: Convergence comparison of two algorithms

As shown in Fig. 4, the RE, Fper and times of the two algorithms are designed, as shown in Tab. 3.

**Table 3:** Target optimization value and calculation time of the two algorithms

Algorithm	RE (%)	Fper (note/h)	Times (s)
BN-PSO	64.57	1.9457	88.42
PSO	62.78	2.4951	96.5

As shown in above Tabs. 2 and 3, the number of iterations of the multi-layer agent power grid fault self-healing system is 27, which is faster than the 30 iterations of the PSO algorithm; besides, the PSO algorithm has a good effect in finding the optimal value within 30 iterations, but after 30 iterations, the target value develops to the local optimal value. BN-PSO algorithm, in combination with the early advantages of PSO algorithm, can quickly find the target value, and carry out 30-40 times in the middle stage, eliminating the edge optimal solution and local optimal solution, so that the target value develops towards the global optimal direction. It is worth mentioning that BN-PSO algorithm solves the problem that PSO algorithm is easy to fall into local optimum, and takes advantage of PSO algorithm, such as fast convergence speed and short calculation time, to improve the efficiency of power grid fault self-healing. Furthermore, the optimized BN-PSO algorithm limits the local optimal threshold value to 35.43%, which not only shortens the calculation time by 35%, but also improves the calculation accuracy by 10%, so that the final failure self-healing rate remains above 95%. Therefore, the power grid fault self-healing system based on multi-agent technology overcomes the shortcomings of particle swarm optimization algorithm, greatly improves the power grid fault self-healing rate, maintains the stability of the power grid, and reduces the economic losses of power enterprises.

## 5 Conclusion

This work proposes a fault self-healing algorithm based on multi-agent technology. It solves the problems of network learning and parameter adjustment in the later stage that particle swarm optimization algorithm falls into the dilemma of local extremum in the later stage, and realizes multi-dimensional nonlinear optimization of main power grid and sub-power grid. The feasibility of integrating Bayesian network and particle swarm algorithm into the model is verified by Matlab software. BN algorithm uses particle swarm optimization algorithm for quick convergence in the early stage to make up for the deficiency of local extremum in the later stage. The results of simulation analysis show that the optimized algorithm has a fast convergence speed in the early stage and is not easy to fall into the local convergence.

The optimal values of RE and Fper are 95.34% and 2.14%, respectively, which indicates that the fault handling efficiency and loss rate are ideal. Simultaneously, according to the fault setting conditions, the main power grid priority or subordinate power grid priority strategy is selected to greatly improve the self-healing ability of the power grid.

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**Conflicts of Interest:** The authors declare that they have no conflicts of interest to report regarding the present study.

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