



Cross Station-Voltage-Level Route Planning Algorithm for System Protection Services in UHV Grid

Danyang Xu^(✉), Peng Yu, Wenjing Li, Xuesong Qiu,
and Luoming Meng

State Key Laboratory of Networking and Switching Technology,
Beijing University of Posts and Telecommunications,
Beijing 100876, People's Republic of China
623094588@qq.com

Abstract. Since the current route planning algorithms for system protection service in communication network fail to consider the situation of station voltage level crossing in ultra-high voltage grid, based on immune algorithm, a planning algorithm is proposed in this paper to lower the network operational risk by ensuring the voltage level balance degree and main-backup route similarity are both as small as possible. Firstly, the risk of node and link is analyzed to derive the network risk balance degree index, and secondly, the cross station-voltage-level planning problem model is established with the consideration of impact brought by station voltage level crossing and route similarity, and then it is solved utilizing IA. Finally, the experimental result shows that the planning algorithm proposed in this paper can lower the network risk, station voltage level balance degree and the route similarity effectively, which provides a useful reference while planning service routing.

Keywords: Service route planning · Immune algorithm · UHV grid · Risk balance

1 Introduction

Due to the construction and expansion of UHV grid in China, traditional power system protection strategies and methods have gradually failed to meet the needs. Thus system protection using the latest information communication and protection control technologies is proposed based on profound characteristics changes of the transitional power grid, and its high reliability is built by strengthening the first defense line, expanding the second defense line, and connecting the third defense line to achieve high-security new generation of large-scale UHV grid defense system.

In order to realize this kind of intelligent protection for UHV power transmit grid, the dedicated real-time high-speed power communication network supporting system protection services, such as relay protection services and stability control services etc.,

is constructed. The most striking feature of the system protection service is that its source and terminal stations are almost high-voltage level. It should be aware that the station in this paper does not mean substation but network equipment in it, which is used for communication. There are main and backup routes for each system protection service, and it will not change readily once set up to ensure the stability of the system, thus, reasonable planning of service routes is the key to not only achieve fast and reliable transmission of services but also improve the utilization of communication resources and reduce the risk of the communication networks.

There are some researches on the routing planning problem of power communication networks at present. Liu et al. proposes a non-uniform service routing energy model for the typical structure of power communication network, which considering the service importance and its configuration method [1], but it does not consider the importance of nodes and links. Huang et al. combines the pressure of service transmission channels and the special constraints of power communication network and proposes a maximum disjoint main-backup routing mechanism based on multi-condition constraints [2], however it does not consider the delay characteristics of the services, and its consideration of service risk is insufficient. He et al. adopts the improved maximum disjoint dual routing algorithm for planning [3], but neither the reliability nor the time domain was considered, what's more, it is ineffective while more factors appear.

It is necessary to transmit services through the low voltage level station while there is no direct communication line laid between the high voltage level stations in most of UVH grid scenarios in China, thereby causes station-voltage-level crossing. In general, the lower the voltage level, the weaker the protection measures, and the greater the risk of carrying critical services on it. But these above-mentioned power communication network routing researches rarely have a consideration for this situation. Therefore, an in-depth cross station-voltage-level route planning approach is needed to strengthen the system operational security and reliability.

In view of the shortcomings of the existing research and the needs of system protection services, an intelligent cross station-voltage-level route planning algorithm considering the UHV's roundabout risk for system protection services in UHV grid is proposed in this paper. As a new type of artificial intelligence algorithm, immune algorithm, which is suitable for dealing with complex problems, has a big advantage over global search and has a good application prospect in optimization problems [4]. The follow-up structure of this paper is organized as follows: Sect. 2 derives the network risk balance degree index considering node and link risk, designs the voltage level balance degree and routing similarity index, and further establish the mathematical model of route planning. Section 3 proposes a main-backup route planning algorithm based on the immune algorithm to solve the problem. Section 4 utilizes the proposed algorithm to plan the service routes in a specific scenario and compares the optimal main-backup routes obtained by the proposed algorithm with the k-shortest path (KSP) algorithm and the maximum disjoint routing (Bhandari) algorithm. The scenario is excerpted from a partial communication topology in China. Section 5 concludes this paper and points out the future work.

2 Modeling of Planning Problem

In UHV grid, the higher the voltage level of the station, the farther the transmission distance is. The UHV DC transmission distance is about 1000 km [5]. Source and terminal stations of the system protection service are high-voltage levels, but sometimes communication with each other requires low voltage level stations for transit. The lower the voltage level of the passing station, the shorter the distance of transmission, the more stations will be needed. Relatively speaking, stations with high voltage level are better protected. Due to a large number of services transmitted by low voltage level stations and high risks, once a fault occurs, the impact is also greater. Therefore, it is necessary to select stations with similar voltage levels to transmit long-distance system protection services. In this paper, considering the factors of network risk, voltage level balance degree, and similarity of main and backup routes, a cross station-voltage-level route planning algorithm for UHV system protection service is proposed, which is the max disjoint main and backup routes for all services in the system protection communication network to ensure the safe and stable operation of the communication network and the power grid.

In the system protection communication network, the nodes are generally various stations of the power grid, and the links are generally communication optical cables between the stations. In order to facilitate the research, the power communication network is abstracted into an undirected connectivity graph $G(V, E)$ according to the graph theory method, where V represents the node set, E represents the link set, and the number of links is $|E| = M$, the number of nodes is $|V| = N$. The service set $S = \{s_1, \dots, s_k\}$ represents all the power communication network services carried on the network G , and the route of the service is the node and the link set passed by the source node v_s to the terminal node v_d .

2.1 Network Risk Model

Node Risk and Link Risk. The node and link, which are the basis for assessing the network risk, play a vital role to guarantee the stability running of service in power communication network. Their respective risk indexes contain the probability of failure and the risk impact on the network after a failure [6]. According to the risk definition, the risk index of node v_i and link e_{ij} can be expressed as

$$R_i^V(t) = P_i^V(t)I(v_i) \quad (1)$$

$$R_{ij}^E(t) = P_{ij}^E(t)I(e_{ij}) \quad (2)$$

Where $P_i^V(t)$ and $P_{ij}^E(t)$ are the probabilities of node and link failure, respectively. $I(v_i)$ and $I(e_{ij})$ are risk impact of link and node failure, respectively. We utilize the service pressure and importance of node and link to reflect impact.

Failure Risk Impaction. In the power communication network, since each node and link carry different types and different numbers of services, it is necessary to consider the

service distribution influence on network risks. Besides, there are differences of importance degree between different nodes and links. The severity of the fault events is different, and the impact degree on the network operational level is also different. To analyze the impact of failure, we will evaluate the impact from two aspects: service pressure and communication equipment importance degree. The formulas are as follows.

$$I(v_i) = D(v_i)NP(v_i) \quad (3)$$

$$I(e_{ij}) = D(e_{ij})NP(e_{ij}) \quad (4)$$

Where $D(v_i)$, $D(e_{ij})$ are the importance degree of node and link, respectively. $NP(v_i)$, $NP(e_{ij})$ are the service pressure of node and link, respectively.

Service Pressure. Various power communication services have different influences on the safe and stable operation of the power system, and the security requirements are also different [7]. Service importance degree is a vital evaluation index for analyzing the impact of power communication services on the power grid [8], which can be quantified with the type of business. For example, if the relay protection service and the security and stability control service only lose a small flow, it may bring huge troubles to the power system. So, the higher the importance degree of service the more serious impact on the power grid its interruption.

The service pressure of node/link is introduced to indicate the impact while fault occurs. The node's service pressure index $NP(v_i)$ and the link's service pressure index $NP(e_{ij})$ are concerned with the number of services carried on each node and each link as well as the importance of the service. If the index is higher, the service carried on each node and each link is more important, the distribution of the service is more unevenly, the failure consequence is worse, and the risk is higher. They can be expressed as:

$$NP(v_i) = \sum_{s_k \in V_{S_i}} n_i^V(s_k) \cdot Z_k \quad (5)$$

$$NP(e_{ij}) = \sum_{s_k \in E_{S_{ij}}} n_{ij}^E(s_k) \cdot Z_k \quad (6)$$

Z_k is the service importance of the service type k , $n_i^V(s_k)$ and $n_{ij}^E(s_k)$ are the services number of the service type k carried on the node v_i and link e_{ij} , and V_{S_i} and $E_{S_{ij}}$ are the service types carried on the node v_i and link e_{ij} , respectively.

The pressure indexes consider the difference of the service importance and the service number carried on the nodes and links, which evaluates the risk impacts of the services reasonably.

Communication Equipment Importance Degree. Studies have shown that it often leads to the collapse of the entire power communication network after some important nodes and links are attacked and failed in the power communication network [9]. The higher the position of the nodes or links in the network topology, the greater the impact of the fault. Therefore, we utilize node importance degree and link importance degree to assess the critical degree of nodes and links, which can reasonably reflect their position in the network.

The stations with different voltage levels may have different ranking and different importance degree. For example, a 500 kV station that has a higher voltage level than a 220 kV station, has a higher importance degree, because the service's security running on the 500 kV station has larger impact on the stable operation of power system. So, node importance degree is concerned with the node voltage level, and link importance degree is also concerned with the node voltage level at both ends.

In addition, the betweenness of node $B(v_i)$ is defined as the proportion of the number of shortest paths through v_i relative to the number of the all shortest paths in the network [10]. It is more accurate and reasonable that node utilizes the betweenness as an important index to reflect its importance degree. Link utilizes $B(e_{ij})$ to reflect its importance degree as well.

Based on the above analysis, we evaluate node importance degree from two aspects: the voltage level of the node and the betweenness of node.

Since the betweenness of node and voltage level belong to different dimensions, normalization is required. Suppose that there are stations with different voltage levels in the network, record as a set $L = \{l_1, l_2 \dots l_z\}$, and $l_i \in L$ is different voltage values (unit: kV). In this paper, the Min-Max standardization method is used to normalize different levels of stations, as follows:

$$w_i = \frac{l_i - l_{\min}}{l_{\max} - l_{\min}} \tag{7}$$

Where, l_{\min} and l_{\max} are the minimum and maximum values of the station voltage, respectively, and w_i is the normalized value for l_i .

Combined with the analysis of the node importance impact indexes, the node importance $D(v_i)$ can be obtained as follows:

$$D(v_i) = \sum_{i=1}^N w_i B(v_i) \tag{8}$$

Where N is the node number, w_i is the voltage level, and $B(v_i)$ is the betweenness of node.

We evaluate link importance degree from two aspects: (1) the voltage level at both ends of the link, (2) the betweenness of link. Normalization processing is described in the same Eq. (7), and the link importance degree $D(e_{ij})$ can be obtained as follows:

$$D(e_{ij}) = \sum_{i=1}^M \max\{w_i, w_j\} B(e_{ij}) \tag{9}$$

Where M is link number, w_i and w_j are the voltage level at both ends of the link, $B(e_{ij})$ is the betweenness of link.

The node and link importance indexes consider the betweenness and voltage level which can reasonably describe their importance.

Network Risk Balance Degree. The balance degree of risk distribution of node and link in the network can reflect the relative rationality of the network configuration. The large value of the network risk balance degree indicates the risk are distributed unevenly, that is, the risk is excessively concentrated. If the node or link with high-risk faults, it will have a major impact on the services in the network. Therefore, we evaluate the overall network risk $RBD(t)$ at time t with the risk balance degree of nodes and links, which is defined as follows.

$$RBD(t) = \sqrt{\frac{1}{N} \sum_{v_i \in V} \left(R_i^V(t) - \overline{R_i^V(t)} \right)^2} + \sqrt{\frac{1}{M} \sum_{e_{ij} \in E} \left(R_{ij}^E(t) - \overline{R_{ij}^E(t)} \right)^2} \quad (10)$$

$$\overline{R_i^V(t)} = \frac{1}{N} \sum_{i=1}^n R_i^V(t) \quad (11)$$

$$\overline{R_{ij}^E(t)} = \frac{1}{M} \sum_{i=1}^M R_{ij}^E(t) \quad (12)$$

Where $\overline{R_i^V(t)}$ and $\overline{R_{ij}^E(t)}$ are the average cost value of the nodes and links risk balance degree, respectively. N is the number of nodes, and M is the number of links.

2.2 Voltage Level Balance Degree

According to the characteristics of cross station-voltage-level of the system protection services, we select stations with same voltage level for each service as much as possible in the route planning. In this paper, the sum of the voltage level's standard deviations of nodes that each service passes through is regarded as the measure of the cross-impact of the node's voltage level. This index called the routing voltage level balance degree $VBD(t)$, has the following formula:

$$VBD(t) = \sum_{s_k \in S} \sqrt{\frac{1}{n} \sum_{i=1}^n (w_i - \overline{w_i})^2} \quad (13)$$

Where w_i is the normalized voltage level of the node that each service passes through, $\overline{w_i}$ is the average of the normalized voltage levels of the node that each service passes through, and n is the number of nodes that each service passes through.

2.3 Similarity Between Main and Backup Routes

The dual-route configuration is to further ensure the reliability of the service. When the main route fails, the system can quickly switch to the backup route, rising the ability to tackle emergencies and ensure the network security and reliability running. If the main route and backup route are dissimilar or approximately dissimilar, the above advantages can be maximized [11]. The main and backup routes may contain the same nodes

and links that cannot be avoided, we try to select the most different main and backup route. We utilize similarity to represent the relationship between the main and backup routes. Because main and backup routes with higher similarity have more common elements, failure probability at the same time is extremely higher and the service risk is higher as well. The similarity of main and backup routes is determined by the link similarity and the node similarity. In reality, the probability of link failure is much higher than the probability of node failure [12], so we only consider the link similarity. The formula is as follows:

$$SD_k = \frac{2 \times ol_k}{l_k} \tag{14}$$

Where SD_k is the routing similarity of the service type k , ol_k is the number of overlapping links of main and backup routes, and l_k is the total number of links of the main and backup routes.

2.4 Objective Functions

In order to reduce the operational risk of the network, we propose a route planning algorithm. For main route, we consider the impact of service pressure and node and link importance degree. Besides, the characteristics of voltage level crossing of the node are considered as well. Then, the minimum weighted sum of the network risk balance degree and voltage level balance degree is formulated as the objective functions of the main route:

$$P(m) = \min[\alpha RBD + (1 - \alpha)VBD] \tag{15}$$

s.t. $\forall s_k, t_k^\gamma \leq T_{\max}^k$

t_k^γ is the main route time delay of the service s_k , T_{\max}^k is the max time delay of service s_k . For backup route, besides considering the same objective of the main route, it is necessary to take additional consideration for the relationship between main and backup routes, and select the backup route with the lowest similarity to the main route. The objective function of the backup route is as follows:

$$P(b) = \min \left\{ [\alpha RBD + (1 - \alpha)VBD] \times e^{\sum_{s_k \in S} SD_k} \right\} \tag{16}$$

s.t. $\forall s_k, t_k^\phi \leq T_{\max}^k$

t_k^ϕ is the backup route time delay of service s_k .

3 Route Planning Algorithm

3.1 Description of Planning Algorithm

The analysis shows that the main and backup routing planning is an NP-Hard problem [13]. For such problems, the shortest path algorithm cannot give an effective planning scheme in the limited time, but the artificial intelligence algorithm performs well. Among them, the immune algorithm, as an artificial intelligence algorithm, has advantages in time convergence and stability [14]. Therefore, we propose a main and backup route planning algorithm based on immune algorithm. Because main and backup route planning objectives are different, we utilize the immune algorithm to plan the main route for all services firstly, map the main route of the service to the graph G secondly, and then utilize the immune algorithm to plan the backup route of all services again. The procedure of cross station-voltage-level main and backup route algorithm is:

Step 1. Abstract the power communication network as $G(V, E)$ utilizing graph theory, where V is a set of nodes and E is a set of communication links.

Step 2. Set the service list $S(v_s, v_d, p_1, p_2)$, where v_s, v_d are the source and terminal node respectively; p_1, p_2 are the main and backup routes respectively.

Step 3. Take $P(m)$ as the planning objective, the service time delay does not exceed the upper limit as constraint, the optimal main route for each service in S is selected through immune algorithm.

Step 4. Output the main route for each service, as well as the $RRD(t)$ and $VBD(t)$, and get a new topology G' .

Step 5. For G' , takes $P(b)$ as the planning objective, the latency of service does not exceed the upper limit as the constraint, and the IA is utilized again to select the optimal backup route for each service in S .

Step 6. Output the backup route for each service, as well as the $RRD(t)$ and $VBD(t)$.

3.2 Procedure of Immune Algorithm

The procedure of the immune algorithm utilized in this paper is described as follows.

Step 1: Set the algorithm parameters. The antibody population size is set to N_q and the number of memory cells is set to N_m , and the maximum iteration is max .

Step 2: Initialize the antibody population. The data of the system protection communication network to be planned is imported, and N_q antibodies are generated as the initial antibody group $A(t)$, and the index of iterations t is set to 0. At this time, the memory is empty and needs to be generated randomly.

Step 3: Calculate the affinity and similarity between each antibody and the antigen in the above antibody population, and then calculate the antibody concentration Con and the selection probability P_a . The N_m antibodies with the best affinity were stored in the memory antibodies.

Step 4: Immunization. The selection probability of each antibody in the antibody group $A(t)$ is calculated and ranked in descending order of the selection probability P_a , and the first N_x antibodies were taken as the parent population $F(t)$. Then the parent antibody group is cloned, mutated, and then the local vaccine is injected proportionally

to generate a new antibody population. Finally, the memory antibody in the memory library is added to form a new antibody group $A(t + 1)$.

Step 5: Evaluation. If $t = \max$, output the optimal solution $A(t)$; otherwise, set $t = t+1$, and then back to step 3.

3.3 Antibody Encoding

The antibody is encoded by natural number coding, and each service route is regarded as a gene of the antibody. The length of the antibody is the number of the service, and each possible optimization strategy corresponds to one antibody. Since the number of nodes and links included in the main and backup routes is unknown, the variable length antibody coding method is utilized in this paper. The first of the antibody gene is encoded as the source node of the service, and the next code is randomly selected from the nodes connected to it, and the process is repeated until the terminal node of the service is reached. For example, the antibody gene of a certain service from the source node S to the terminal node D is encoded as $SN_1N_2N_3\dots N_i D$.

3.4 Antibody Evaluation

Affinity. The affinity between antibody and antigen is used to evaluate the superiority of the antibody. In this problem, affinity functions of antibody in main and backup routes are different based on their optimization objective.

The affinity function S_a in main route is determined by the network risk and the voltage level balance degree, which is defined as follows:

$$f(S_a) = \frac{1}{P(m)} = \frac{1}{\alpha RBD(S_a) + (1 - \alpha)VBD(S_a)} \tag{17}$$

Similarly, the affinity function S_a in backup route is determined by the network risk, voltage level balance degree and routing similarity, which is defined as follows:

$$f(S_a) = \frac{1}{P(b)} = \frac{1}{[\alpha RBD(S_a) + (1 - \alpha)VBD(S_a)] \times \sum_{e^k \in S} SD_k} \tag{18}$$

Antibody Concentration. In order to avoid the algorithm to select the antibody with high similarity and fall into local optimization, this paper introduces the antibody concentration function [15]. The similarity between antibody S_a and antibody S_b is as follows:

$$Ratio(S_a, S_b) = \frac{f(S_a)}{f(S_b)} \tag{19}$$

The concentration $Con(S_a)$ of antibody S_a indicates the ratio of the antibody similar to S_a in antibody population and reflects the diversity of the antibody population. The formula is as follows.

$$Con(S_a) = \frac{\sum_{b=1}^{N_q} Sim(S_a, S_b)}{N_q} \quad (20)$$

$$Sim(S_a, S_b) = \begin{cases} 1, & 1 - \gamma \leq Ratio(S_a, S_b) \leq 1 + \gamma \\ 0, & \text{Otherwise} \end{cases} \quad (21)$$

Where N_q is the total number of antibodies, and $Sim(S_a, S_b)$ indicating whether the antibody S_a and the antibody S_b are similar. When there is any positive number γ such that $1 - \gamma \leq Ratio(S_a, S_b) \leq 1 + \gamma$ is satisfied, the antibody S_a is treated as similar with S_b , and thus $Sim(S_a, S_b)$ is 1, otherwise, it is 0.

3.5 Details of Immune Algorithm Solver

Clone. Clone the parent antibody population $P(t)$, and each antibody produces h copies to form a new population.

Variation. After cloning operation, some genes on the antibody are randomly altered with a small probability of mutation. The variation process designed in this paper is that a node from a certain antibody gene is regarded as a mutation point, but the source node and the terminal node of the service route are not regarded as mutation points. Then the route from the source node to the mutation point is guaranteed to be unchanged. The nodes connected with the mutation point are randomly selected till the terminal node.

Selection. It is necessary to ensure that antibodies with higher affinity are selected with greater probability when selecting antibodies, and the diversity of the progeny population should be ensured to avoid premature convergence. The selection operator is determined by the affinity between the antibody and the antigen and the antibody concentration. The greater the affinity of the antibody, the smaller the concentration, the greater the probability of being selected. Therefore, the selection probability of the antibody S_a is defined as follows:

$$P_a(S_a) = \frac{f(S_a)}{Con(S_a)} \quad (22)$$

Vaccine Extraction and Injection. The extraction and injection of the vaccine is carried out after each iteration. Extract the fixed gene sequence of the optimal antibody, and then inject into the antibody population in proportion, which can effectively suppress the degradation phenomenon in the mutation process and speed up the algorithm convergence.

4 Experimental Details

In order to verify the effectiveness of the proposed planning algorithm, we utilize the topology of the communication network in a certain region of China to conduct simulation experiments. Plan the main and backup routes for each service, and the network topology is shown in Fig. 1. There are three types of stations in the network, namely 1000 kV station, 750 kV station and 500 kV station, 33 nodes and 45 communication links. The network carries eight services, its specific data is shown in Table 1, and service importance degree is set according to [15].

Table 1. Service details

Service	Source	Terminal	Service importance
1	1	18	3
2	3	25	10
3	29	16	6
4	29	19	5
5	4	12	5
6	5	20	3
7	8	26	6
8	15	18	1

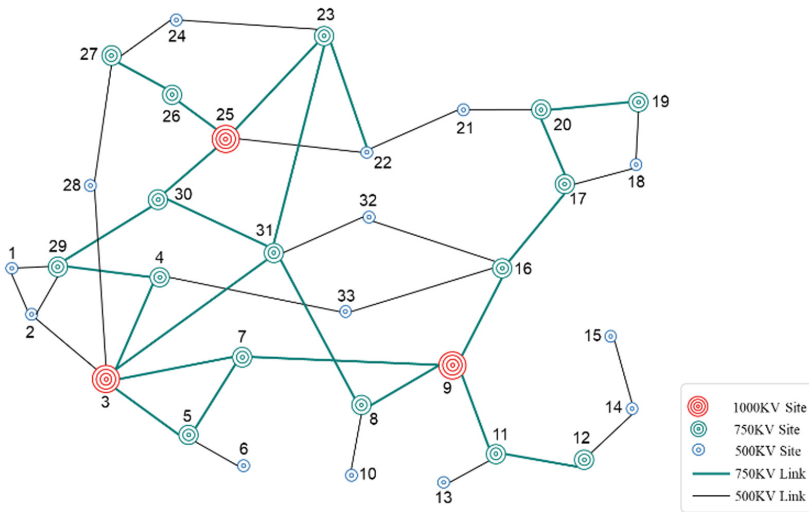


Fig. 1. Partial communication network topology in China

We collect various data from the network management equipment of the system protection communication network, including the time delay, the related fault records, etc. With the data, the failure probability of each node and link can be obtained according to the method in [16]. The planning algorithm proposed above is used to perform service routing planning for the foregoing services. In the immune algorithm, the antibody length is 8, the initial antibody population is set to 200, the number of memory cells is set to 20, the number of iterations is set to 300, the crossover rate is set to 0.8, and the mutation rate is set to 0.2, α is set to 0.5 while calculating affinity.

Compare the optimal main and backup routes obtained in this operation with the routes generated through the k-shortest path (KSP) algorithm [17] and the maximum disjoint routing (Bhandari) algorithm [3]. The main routing results are shown in Table 2, and the backup routing results are shown in Table 3.

Table 2. Main route planning result comparison of three different algorithms

S_i	KSP	IA	Bhandari
1	1, 29, 4, 33, 16, 17, 18	1, 29, 4, 33, 16, 17, 18	1, 29, 4, 33, 16, 17, 18
2	3, 2, 29, 30, 25	3, 31, 23, 25	3, 2, 29, 30, 25
3	29, 4, 33, 16	29, 30, 31, 32, 16	29, 4, 33, 16
4	29, 30, 25, 22, 21, 20, 19	29, 4, 33, 16, 17, 20, 19	29, 30, 25, 22, 21, 20, 19
5	4, 33, 16, 9, 11, 12	4, 29, 30, 31, 8, 9, 11, 12	4, 33, 16, 9, 11, 12
6	5, 7, 9, 16, 17, 20	5, 7, 3, 28, 27, 24, 23, 22, 21, 20	5, 7, 9, 16, 17, 20
7	8, 31, 30, 25, 26	8, 31, 23, 24, 27, 26	8, 31, 30, 25, 26
8	15, 14, 12, 11, 9, 7, 3, 28	15, 14, 12, 11, 9, 8, 31, 23, 24, 27, 28	15, 14, 12, 11, 9, 7, 3, 28
AVG delay	0.382 ms	0.415 ms	0.382 ms
Affinity	0.0026	0.0039	0.0026

From Tables 2 and 3, it can be seen that the number of nodes and the average delay of the planning algorithm proposed in this paper may be more than other two algorithms. This is because the planning algorithm comprehensively takes the network risk, voltage level balance degree and routing similarity into consideration, while the KSP algorithm and the Bhandari algorithm only consider the time delay so that the average time is smaller. In addition, the affinity of the optimal solution for the main and backup routes obtained by the planning algorithm is better than the other two algorithms significantly. Although the number of nodes and the average delay of the proposed algorithm is the largest, still satisfy the delay constraint. The indexes are compared among our algorithm and other two algorithms, as shown in Figs. 2 and 3.

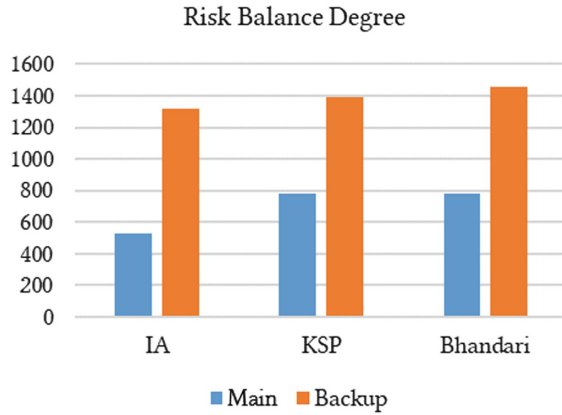


Fig. 2. Main-backup routing indexes (*RBD*)

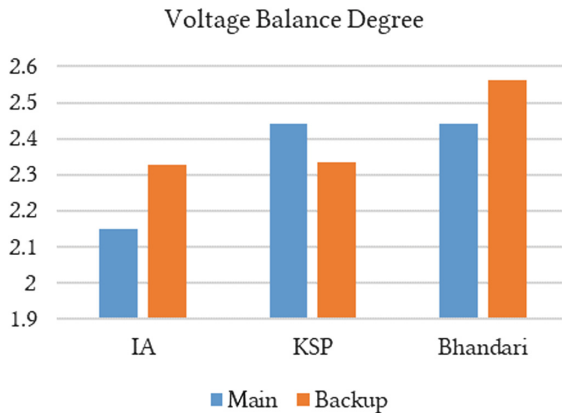


Fig. 3. Main-backup routing indexes (*VBD*)

The risk balance degree figure is a comparison of the *RBD* utilizing three algorithms. As for network risk, that of planning algorithm is the smallest and is decreased by 27% and 29% compared with the KSP algorithm and the Bhandari algorithm, which reflects the effectiveness of this algorithm. The figure on the right is a comparison of the *VBD* utilizing three algorithms. As for voltage level balance degree, it is reduced by 6% and 9% compared with the KSP algorithm and the Bhandari algorithm, which is also superior to the other two algorithms. Comparison of the similarity of main and backup routes of each service generated utilizing three algorithms is shown in Fig. 4.

From Fig. 4, it can be seen that the routing similarity of the 1st, 2nd, 3rd, and 7th services obtained by the planning algorithm are 0, and the similarities of the 4th, 5th, 6th, and 8th services are 0.11, 0.15, and 0.11, 0.29, respectively, which guarantee the maximum dissimilarity of the main and backup routes basically. The sum of the similarity of each service obtained by the planning algorithm, KSP algorithm, and

Table 3. Backup route planning result comparison of three different algorithms

S_i	KSP	IA	Bhandari
1	1, 29, 30, 31, 32, 16, 17, 18	1, 2, 29, 30, 31, 23, 22, 21, 20, 19, 18	1, 2, 29, 30, 25, 22, 21, 20, 19, 18
2	3, 2, 1, 29, 30, 25	3, 4, 29, 30, 25	3, 28, 27, 26, 25
3	29, 30, 31, 32, 16	29, 4, 33, 16	29, 30, 31, 32, 16
4	29, 4, 33, 16, 17, 18, 19	29, 30, 31, 23, 24, 27, 26, 25, 22, 21, 20, 17, 18, 19	29, 4, 33, 16, 17, 18, 19
5	4, 3, 7, 9, 11, 12	4, 29, 1, 2, 3, 28, 27, 24, 23, 22, 21, 20, 19, 18, 17, 16, 32, 31, 8, 9, 11, 12	4, 3, 7, 9, 11, 12
6	5, 3, 31, 32, 16, 17, 20	5, 7, 9, 8, 31, 32, 16, 17, 18, 19, 20	5, 3, 2, 29, 30, 25, 22, 21, 20
7	8, 31, 23, 25, 26	8, 9, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26	8, 9, 7, 3, 28, 27, 26
8	15, 14, 12, 11, 9, 7, 5, 3, 28	15, 14, 12, 11, 9, 7, 5, 3, 2, 1, 29, 4, 33, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 28	15, 14, 12, 11, 9, 8, 31, 30, 25, 26, 27, 28
AVG delay	0.408 ms	0.533 ms	0.447 ms
Affinity	0.00059	0.0024	0.00059

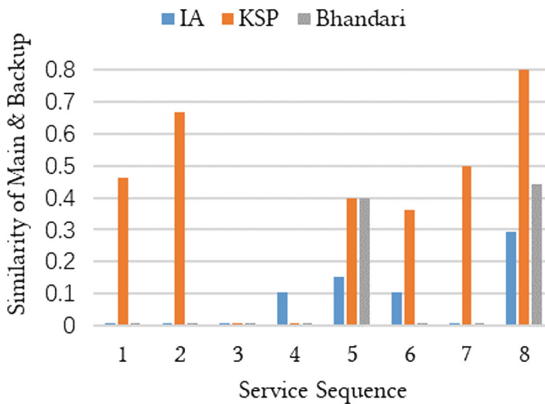


Fig. 4. Main-backup routing similarity

Bhandari algorithm is 0.65849, 3.1918, and 0.84444, respectively, which reflects the similarity of planning algorithm is greatly decreased compared with the KSP algorithm and is also better than the Bhandari algorithm. Although the KSP algorithm and the Bhandari algorithm have the smaller average delay, they can't plan the optimal main and backup routes from multiple aspects. Therefore, there is a large gap between the planning algorithm and other two algorithms.

Figure 5 shows the optimal solution in the antibody population after each iteration in this simulation. In this case study, the max number of the iteration is 300. And when the number of the iteration is around 50 and 250, the optimal solutions of main and backup routes is almost stable, which shows the planning algorithm has good convergence.

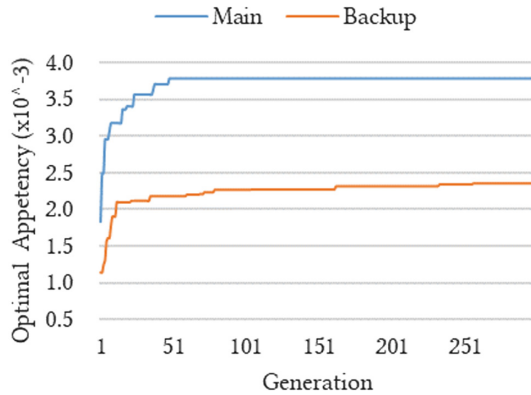


Fig. 5. Convergence graph of our algorithm

In summary, after the above analysis, the cross station-voltage-level planning algorithm can select main and backup routes with minimized risk and routing similarity under the constraint of delay, so as to reduce the overall operational risk of the network and provide a useful reference for network resource allocation optimization and service routing planning.

5 Conclusion and Future Works

Considering the UHV's roundabout risk level, this paper proposes a route planning algorithm based on immune algorithm for UHV communication network. Through considering the three major influencing factors, including network risk, voltage level balance degree and routing similarity, and constraint of the service delay, construct the cross station-voltage-level planning model and verify the effectiveness of it by simulation experiments. It has strong application value in routing planning and risk management of power communication network.

However, there are some imperfections in this paper. In the simulation experiment, it only considers that the source node and the terminal node are the same voltage level, and ignore the voltage level difference between them. Besides, the index lacks a unified evaluation scale. It is difficult to directly quantify and compare the evaluation results of different networks. The next step will be to consider the communication network routing planning problem with service endpoints at different voltage levels and establish a reasonable and standardized risk standard.

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