An Improved Ant Colony-Based Alternate Path Selection Method for Wide-Area Protection System in Optical Communication Network of Power Grid

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Abstract. Wide-area protection system has a strict requirement on real-time and reliability of communication network. Currently, the path selection algorithm that meets the requirements of wide-area protection system communication can calculates an optimal master path while meeting the requirements on real-time and reliability. After some link or node in the master path fails, the router in the communication network can detects the fault of the link or node and needs to re-calculate a transmission path and re-release the path information. Unfortunately, the sum of the fault detection time, the new path calculation time and the update time of new path has exceeded the tolerance delay of wide-area protection system. For solving this problem, 1 + 1 protection scheme is proposed in this paper. We employs an improved ant colony algorithm to calculate the master path and the alternate path, which meet the real-time and reliability requirement of wide-area protection system. As soon as the master path fails, it will immediately launch the alternate path, so that it can save the delay spent in detecting the fault of link or node and re-release the path information. Finally, a case study is carried out and it is proved that the improved ant colony can find the optimal master and alternate paths.

Keywords: Wide-area protection system · Path selection · Alternate path · Ant colony

1 Introduction

Relay protection system is an important part in power system. Most of conventional protection systems only collect local or limited fault information, which bring negative effect on the selectivity and fastness of protection for complex power system. The Wide-Area Protection System (WAPS) can obtain global information from the power system. At the same time, from the global perspective of the entire system, the stability, selectivity, accuracy and reliability of the protection system are improved. Furthermore, WAPS has potential to take coordinated measures to avoid the cascade trip-off or black out of power system [1, 2]. Initially it was proposed to avoid the long-term voltage collapse [3]. In recent years, with the rapid development of power system communication networks, WAPS has received extensive attention from many scholars.

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Wide-area protection systems are one of the key factors in wide area protection. Therefore, the real-time, reliability, security and self-healing of the communication system are strictly required. Especially when the smart grid communication fails, it is also important to select the appropriate path to transmit information to the destination quickly and reliably in the wide area protection system [4].

Currently path selection algorithm mostly adopts the concentrated methods based on graph theory such as Dijkstra or Bellman-Ford algorithm to find the shortest path, which has been extensively used in communication network, such as OSPF in the Internet. Wide-area Protection System has a strict requirement on real-time, reliability and self-healing of communication system. Therefore, many scholars calculates a path selection with QoS parameters such as bandwidth, delay and reliability. The literature [5] propose a robust routing algorithm to reach the higher network energy efficiency, which is based on optimization problem. In [6], it describes how to employ Dijkstra algorithm to acquire the path with the minimum hop count. The literature [7, 8] studies the reliability of power communication network and self-healing after network failure. In [9], an optimization model that maximizes path reliability under constraints of communication delay is established. This literature [10, 11] is to minimize the network's bit energy consumption parameter, and then we propose the energy-efficient minimum criticality routing algorithm, which includes energy efficiency routing and load balancing. For the requirements of wide-area protection communication system, a path selection model based on MPLS to meet the QoS requirements of wide-area protection system is established in [12].

Wide-area protection system has strict requirements on real-time, reliability, self-healing of the communication network. Especially after the master path fails, the communication system still can reliably transmit the data via the alternate path. Above algorithms mainly acquire an optimal master path and several nodes-disjoint or link-disjoint alternate paths, but QoS parameters are not taken into account to meet the requirements of wide-area protection system. The optimal primary path is calculated to meet the real-time and reliability requirements of the path selection algorithm that satisfies the wide-area protection system communication requirements. After some link or node in the master path fails, the router in the network detects the fault of the link or node and needs to re-calculate a transmission path and re-release the path information. Unfortunately, the sum of the fault detection time, the new path calculation time and the update time of new path has exceeded the tolerance delay of wide-area protection system. For solving this problem, 1 + 1 protection scheme is proposed in this paper. We employs an improved ant colony algorithm to calculate the master path and the alternate path, which meet the real-time and reliability requirement of wide-area protection system. As soon as the master path fails, the alternate path will be started immediately, so that it can save the delay spent in detecting the fault of link or node and re-release the path information.

The rest of this paper is organized as follows: multi-path selection model is introduced in Sect. 2; the solution based on improved ant colony for the model is proposed in Sect. 3; the case study and result analysis are carried out in Sect. 4; finally, we conclude in Sect. 5.

2 Multi-path Selection Model

2.1 Path Reliability

In the network topology, each path can be treated as a set of links and nodes. The reliability of the path is affected by the availability of links and nodes. Given there are n paths $path_1\, path_2\, path_{3.} \cdots path_k \cdots path_n$ between source node and destination node, the collection of nodes passed by $path_k$ is $C_{path_k} = \{c_1, c_2, \cdots, c_m\}$, the collection of links is $E_{path_k} = \{e_1, e_2, \cdots, e_{m-1}\}$. Path is made up by nodes and links in the way of series connection, whose reliability is the product of availability rate of each link between nodes times the availability rate of each node. The expression of path reliability is as follows:

$$P_{path_k} = \prod_{i=1}^{m-1} A_{e_i} A_{c_i} \tag{1}$$

P_{path_k} is reliability of $path_k$, n means total number of nodes passed by the path, A_{e_i} means availability rate of the i-th link on $path_k$. A_{c_i} means availability rate of the i-th node on $path_k$.

2.2 Delay

Information transmission delay is mainly determined by factors such as communication media, transmission distance and number of network equipment passed. Total delay of information and data passed along the $path_k$ equals to the sum of transmission delay, treatment delay and queuing delay and the expression for information transmission delay of the path is as follows:

$$T_{path_k} = \sum_{i=1}^{n-1} \frac{d_{e_i}}{\frac{2}{3}v} + t + \Delta t \tag{2}$$

$$t = \frac{1}{\gamma} \sum_{(i,j)} \frac{\lambda_{ij}}{\mu_{ij} - \lambda_{ij}} \tag{3}$$

In the formula, T_{path_k} is the information transmission delay of $path_k$, d_{e_i} is length of link e_i, the transmission velocity of information in optical fiber is 2/3 of velocity of light, namely, 2/3 v, Δt is treatment delay of node, t is the queuing delay of node, λ_{ij} means the birth rate of data package in the queue of link (i, j), namely, the speed of service data package joining the queue, μ means death rate, namely, the speed of service being finished and leaving the queue, and γ is total arrival rate of the system.

2.3 Optimization Model for Path Selection

To meet the requirements of wide-area protection communication, and enhance its reliability by studying the master path and alternate path, an optimization model is established as follows:

$$\begin{cases} \min T(T_{path_1}, T_{path2}, \cdots, T_{path_k}) \\ s.t \quad P(P_{path_1}, P_{path2}, \cdots, P_{path_k}) > P_0 \end{cases} \tag{4}$$

In the above formula, *T(.)* is the network transmission delay of selected path, *P(.)* is the reliability of a path selected from candidate paths. The reliability of power communication network is one of the decisive factors on whether wide range protection can realize its preset function. P_0 is the minimal reliability permitted for transmission of wide range protection information in the power communication network, and if the reliability of the path is larger than P_0, it will be reserved as a candidate path. In the paper, the value of P_0 is set as 0.950. Based on the routine selection mathematical model put forward, several paths with a high reliability and instantaneity are found between designated source node and destination node.

Very high transients are required in wide area protection communication systems. For provincial medium-sized power grids, the central dispatch master station needs to obtain measurement information for all substations within 20 ms. In other words, the time for each substation to issue a master station control command should also be controlled within 20 ms. However, when the host path for information transmission fails, the delay in detecting the path failure and the waiting delay of the reconstructed path often exceed the delay allowed by the wide range of protection on the communication system. Therefore, a channel should be selected to transmit the minimum total delay without crossing any node of the host path to ensure that the standby path is initiated once the host path fails, resulting in reduced fault detection latency and latency. The final delay path reconstruction, the information transmission delay is less than 20 ms.

3 Solution Based on Ant Colony

Based on the basic algorithm of ant colony, modify the expecting factor to establish a model of optimal path. Multiple transmission paths of different quality from source node to destination node are found by improved ant colony algorithm, and select secondary alternate path from them which does not cross with any node of host path. Once the host path for transmission protection and control fails, it can quickly switch to the alternate path, thereby improving the immediacy and reliability of the WRPS. The specific steps of improved algorithm are as follows:

(1) Initialized parameters

Set the initial parameters: number of nodes *n* and number of ants *k*, transition probability of ants P_{ij}^k, intensity of pheromone on the edge *(i, j)* τ_{ij}, motivation degree for node *i* to transit to node *j* is η_{ij}, pheromone volatile parameter α, maximum iterations $N_{C_{\max}}$, delay for ant when passing edge (i, j) T_{ij}, maximum link availability rate on the edge (i, j) is E_{ij}, ρ and ε are parameters introduced by the algorithm.

(2) Put ant k at the source node S.
(3) The ant selects path based on formulas (5), (6) and (7).

$$P_{ij}^{k}(t) = \begin{cases} \frac{\tau_{ij}^{k}(t)\eta_{ij}^{k}(t)}{\sum\limits_{s \in allowed_k} \tau_{is}^{\alpha}(t)\eta_{is}^{\beta}(t)}, & j \in allowed_k \\ 0 & otherwise \end{cases} \quad (5)$$

$$\eta_{ij} = \frac{1}{T_{ij}} \quad (6)$$

$$\tau_{ij}(t+n) = \rho_1 \cdot \Delta\tau_{ij}(t) + \Delta\tau_{ij}(t, t+n) \quad (7)$$

$allowed_k$ means the collection of nodes that can be selected by ant k in the next step, the transition probability $P_{ij}^{k}(t)$ is in direct proportion to $\tau_{ij}^{\alpha}\ \eta_{ij}^{\beta}$. η_{ij} reflects the motivation degree for node i to transition to node j, T_{ij} means the delay for ant when passing edge (i, j), τ_{ij} means pheromone track intensity on the edge (i, j), $\Delta\tau_{ij}$ means the track pheromone per unit length left by ant on the edge (i, j), α and β are two important parameters.

(4) Each path generated by ant will undergo a partial renewal based on formula (8).

$$\tau(r, s) \leftarrow (1 - \rho) \cdot \tau(r, s) + \rho \cdot \Delta\tau(r, s) \quad (8)$$

(5) Before each ant generates a path, it will repeat steps (3) and (4) in cycle.
(6) A whole renewal will be conducted based on formula (9).

$$\tau(r, s) \leftarrow (1 - \alpha) \cdot \tau(r, s) + \alpha \cdot \Delta\tau(r, s) \quad (9)$$

(7) Repeat steps (3)–(6) in cycle until the iterations reach the designated number or there is no better solution after several iterations.
By improving the ant colony algorithm, the performance of the algorithm is improved, the ant's ability to search is also enhanced, and the stagnation of the algorithm is effectively avoided.

4 Case Simulation and Result Analysis

4.1 Case Study

As shown in Fig. 1, the paper takes the network topology of some architecture of Shandong's power grid as an example. The topology comprises 12 nodes and 21 links. In the bracket of node 1 (0.1, 0.998), 0.1 ms means queuing delay of node 1, 0.998 means availability rate of node 1. In the bracket (0.234, 0.997) on the link between node 2 and 3, 0.234 ms means transmission delay of link between node 2 and 3, 0.997 means availability rate of link between node 2 and node 3. Transmission velocity of information in the channel $v = 2 \times 10^8$ m/s, and given the treatment delay of nodes at $\Delta t = 0.1$ ms.

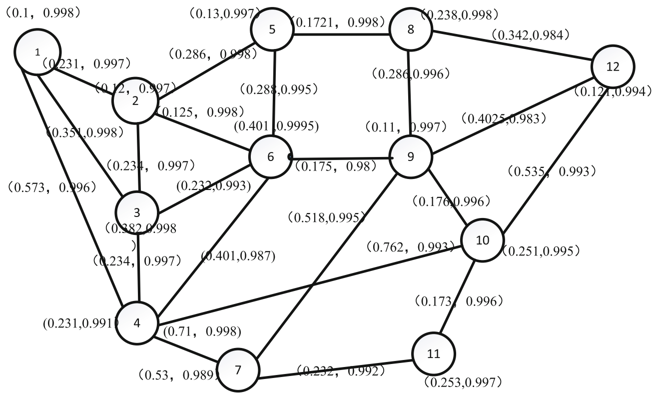


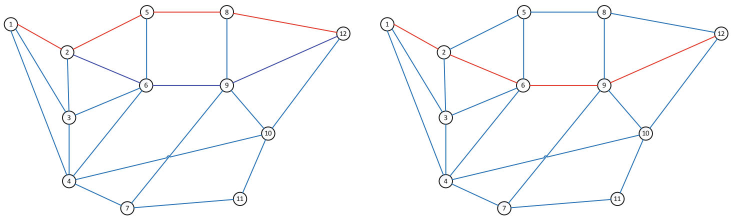
Fig. 1. Network topology

4.2 Simulation Result Analysis

With the parameters of Table 1 and multi-path routine algorithm suggested by the paper, a simulation is conducted in MATLAB. The actual state of link in network topology model is compared with the simulation result of improved ant colony algorithm, which indicates that the path selected by routine algorithm keeps consistent with the actual optimal path. The simulation experiment takes solving host and alternate paths between node 1 (source node) and node 12 (destination node) in Fig. 1, and the Figs. 2, 3, and 4 are optimal path and several secondary paths obtained from the routine algorithm introduced by the paper.

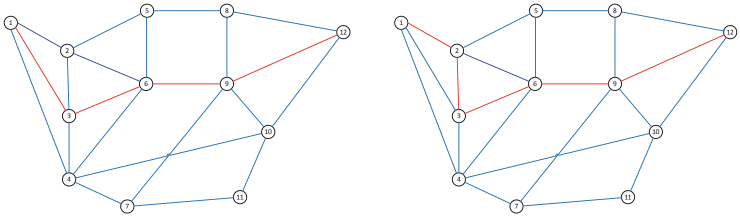
Table 1. Average normalized values of the pheromone of paths.

Path	Nodes	Max delay/ms
Path1	1 → 2 → 5 → 8 → 12	1.5191
Path2	1 → 2 → 6 → 9 → 12	1.5645
Path3	1 → 3 → 6 → 9 → 12	1.9075
Path4	1 → 2 → 3 → 6 → 9 → 12	2.2876
Path5	1 → 4 → 10 → 12	2.3520
Path6	1 → 4 → 10 → 9 → 12	2.5055



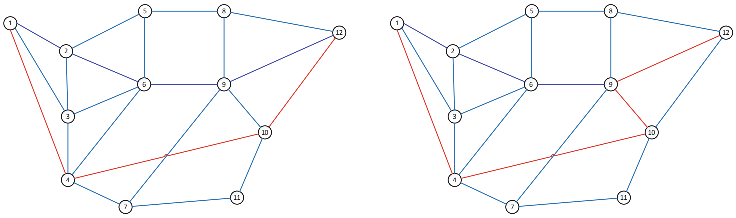
a. Path 1： Optimal path b. Path 2： Secondary path

Fig. 2. The path according to the algorithm of this paper



a. Path 3： Secondary path b. Path 4： Secondary path

Fig. 3. The path by the algorithm of this paper



a. Path 3： Secondary path b. Path 4： Secondary path

Fig. 4. Path algorithm obtained

According to the above three figures, we find the main path and several alternate paths using the algorithm of this paper. According to the picture, several alternate paths are different. The delay results are calculated and analyzed as shown in the following Tables 1 and 2.

Table 2. Parameters of paths in the network.

Path	Reliability	Quality	Path selection
Path1	0.986	1	Host path
Path2	0.989	2	
Path3	0.985	3	Optimal alternate path
Path4	0.990	4	
Path5	0.992	5	Secondary path
Path6	0.898	6	

According to data of Tables 1 and 2, the routine algorithm computes several multi-path routines with different quality from source node to destination node. Path 1 meets the reliability constraint and its path transmission delay is the minimal. Therefore path 1 is taken as optimal path obtained by the routine algorithm, which is the host path for transmission protection and control. The selection of alternate paths will be based on quality sequence, and follow the principle of not crossing with any node of host path, with an attempt to cut the delay for detecting host path fault and delay for reissuing routine list when the host path fails. Path 2 and 4 do not meet the requirement of not crossing with any node of host path 1; Path 6 does not meet the reliability constraint; Path 3 is the secondary path that meets double conditions of not crossing with node of Path 1 and reliability constraint, while with the minimal total transmission delay, so Path 3 is taken as the optimal alternate path for transmission protection and control and path 5 taken as secondary path for the purpose.

5 Conclusion

In this paper, in the network topology model of wide-area protection communication system, an improved ant colony algorithm is used to search several path routines of different quality between source node and destination node, and select the optimal alternate path. The multipathing procedure obtained in this paper enhances the reliability of a wide range of protection communication systems. Once the optimal path routine used by the wide-range protection communication system fails, it will quickly start the secondary standby routine, which can reduce the delay of detecting host path failures and delay the list of re-release routines to meet the requirements of the communication network, and protect reliability and immediacy of the power supply.

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