Research on Optimizing the Recovery Strategy of a Distribution Network Communication System Under Extreme Disasters

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Abstract. Extreme disasters, such as typhoons, cause great damage to distribution network communication systems, affecting the perception of disaster situations and the repair speed of the distribution networks. To realize the rapid recovery of a distribution network, an optimal recovery strategy of the distribution network communication system is proposed in this paper from the perspectives of predisaster prediction and postdisaster rush repair. First, based on multivariate data, the space-time mesh fusion method is used to predict the fault position of the distribution network communication system, guiding the accurate allocation of emergency repair resources, and the fault position is corrected using man-made statistics after a disaster. Then, combining fiber optics, mobile nets and emergency communication vehicles, rush repair rules for the distribution network communication system after extreme disasters are put forward, and the shortest route search algorithm is used to solve the minimum rush repair time under the rules, which is the optimal rush repair scheme for the distribution network communication system after an extreme disaster. Finally, the proposed strategy is applied to a practical topology, and the results demonstrate that the strategy is reasonable and effective.

1. Introduction
In recent years, due to extreme disasters, accidents in distribution network communication systems have occurred frequently, which has seriously hindered postdisaster rush repair work in disaster-influenced areas. In July 2016, typhoon ‘Nibote’ caused a total of 2,784 communication base stations to be retired in Fujian, and many regional communications were interrupted. The command center could not obtain the fault information in time, which seriously delayed the recovery of the distribution network [1]. To improve the recovery ability of distribution networks and reduce the losses caused by disasters, it is of great significance to accelerate the restoration of distribution network communication systems.

At present, existing research on rush repair work in distribution networks, including predisaster failure predictions [2], allocation of repair resources [3], trouble information acquisition after the disaster [4], and the formulation of a repair strategy [5], has formed a mature system. However, such research is based on the complete availability of information and has not yet taken into account the impact of communication system failures. Once a distribution network communication system fails due to extreme disasters, the commander may not be able to obtain the status information in time and thus
cannot make the optimal decision. Therefore, it is necessary to repair the distribution network communication system in a timely manner.

Compared with existing studies, the advantages and contributions of the proposed strategy are as follows: An improved predisaster fault prediction method based on space-time meshes and a postdisaster optimal rush repair strategy coordinated by using fiber optic repair, mobile base stations and emergency communication vehicles are proposed. In terms of predisaster fault prediction, domestic and foreign scholars have used statistical analysis [6] and smart assessment [7] to predict the failure of physical and communication equipment in a distribution network under a single disaster. These methods have received a large amount of research and have matured, but the accuracy of the position of the fault equipment is not fine enough. Moreover, the application of geographic grids lacks time dimensions and has basically been performed for a single disaster type [8], with a lack of judgment of communication equipment failure under multidimensional disaster types; in the postdisaster repair of distribution network communication systems, the applications of fiber optics [9], emergency communication vehicles [10] and mobile nets [11] in electricity emergency communication have been researched, and there is a lack of a combination of wired and wireless communication. Using only fiber optic repair, the recovery speed of the communication system is very slow. Wireless repair has improved the speed of communication restoration, but the particularity of the lifeline load nodes in the distribution network is neglected; such nodes need to be connected to the control center through a cable network. In the process of repairing communication systems, there is a lack of corresponding rush repair principles, mainly relying on human experience to give priority to the restoration of important nodes, which is highly subjective. Under extreme disasters, the operating state of the system changes rapidly, and human judgment alone is bound to lead to problems.

2. Structure of the Power Communication System

As shown in Figure.1, the distribution network communication system layer is similar to the power layer and has a single- or multiple-loop structure. The distribution network communication system includes a control center, communication intermediate nodes, mobile base stations, and normal communication nodes. The 110 kV power node corresponds to a communication intermediate node and is directly connected to the control center. The state data are transmitted in both directions, and the control signal is transmitted from top to bottom in one direction. This signal can only be transmitted from the control center to a communication intermediate node and then transferred to a normal communication node. A mobile base station is a special communication intermediate node. To ensure the security of the business, it can only transmit state data, not control signals [12].

Due to the increasing degree of coupling between the communication system and the power system, after an extreme disaster, the communication system can not only monitor the fault information of the distribution network point-to-point but also facilitate the command center to guide the optimal scheduling of emergency personnel. Once the communication system fails on a large scale, the fault information cannot be obtained in a timely manner, the repair personnel are disorganized, and the repair work cannot be smoothly carried out. Therefore, it is particularly important to restore the communication system. From the perspectives of predisaster prediction and postdisaster emergency repair, the optimal recovery strategy for a distribution network communication system is studied in this paper.
3. A Fast Method for Determining the State of the Communication Network

To speed up the rush repair of the communication system after an extreme disaster, real-time judgment of the fault is required. Due to communication failures, the efficiency of fault information acquisition is very low. Therefore, according to the predisaster prediction, the fault position is initially completed based on the forecast information of extreme disasters, and the allocation of emergency repair resources is guided. Then, after the disaster, the fault position is corrected to guide personnel scheduling.

In terms of predisaster fault prediction, multivariate information, such as geographic information, meteorological information, and communication network structure information, is used to predict the state of the communication network. The amount of multivariate information is large, and the range is wide; it is difficult to process data on a large scale. A method of space-time meshes is adopted in this paper and has the following four steps:

Step 1: Divide the disaster-influenced area into small grids, encode the grids, and quickly obtain the location of each device;

Step 2: Add the time dimension on the basis of the geographic grid and superimpose the forecast disaster and the actual disaster, including the typhoon path, rainstorm information and other multidimensional disaster types, on the geographic grid;

Step 3: Model and analyze the disaster strength and invulnerability of the equipment within the small grids, and predict the probability of equipment failure. Equipment with a failure probability greater than a certain threshold is considered a faulty device. According to the overall communication system failure situation, emergency repair resources are allocated reasonably;

Step 4: According to man-made statistics, the final failure state of the communication system is corrected, which is conducive to accurate repair.

4. Repair Strategy of the Distribution Network Communication System

4.1. The Repair Methods

At present, repair methods of distribution network communications systems mainly use fiber optic repair. With the advantage of safety, this approach can safely transmit control signals, but the speed is slow and it is not conducive to the repair of electricity; in addition, wireless communication of distribution network nodes can be achieved through mobile base stations and emergency communication vehicles. A single mobile base station can replace multiple distribution network communication nodes; this method shortens the recovery time and is conducive to disaster perception. The disadvantages are that the communication nodes restored in this way cannot transmit control signals, and the nodes still need fiber optic repair, which increases the workload.

4.2. The Repair Rules

Priority is given to repairing the communication nodes corresponding to lifeline loads, including hospitals, government buildings, and the water supply, and ensuring that such nodes can be
automatically controlled by the command center. To realize the rapid recovery of the communication system after an extreme disaster, the advantages of comprehensive wireless communication and wired communication are considered. Based on giving priority to repairing the lifeline load communication nodes, the following repair rules for the distribution network communication system are made in this paper: (1) Priority is given to repairing the communication nodes corresponding to lifeline loads, and the method used is fiber optic repair; (2) Mobile base station repair is better than single-communication-node repair; and (3) Emergency communication vehicles give priority to repairing communication intermediate nodes.

4.3. The Repair Targets
After an extreme disaster, the large-scale damage to the communication system affects the disaster perception of the distribution network, which in turn affects the repair speed. Due to the different locations of communication fault nodes, mobile base stations, emergency communication vehicles and repair teams, the task arrangement of repair teams and the repair order of communication nodes will influence the overall optimal recovery goal.

In multifault rush repair of distribution network communication systems, the most important concerns in engineering are the economics and timeliness, which can be equivalent to a two-layer optimization model. The upper target is the lowest cost of the communication system failure, and the lower target is the shortest repair time needed for the distribution network communication system to achieve emergency communication.

\[ Val_{total} = \sum_{i=1}^{m} Val_{i} \cdot t_{i} \]  

(1)

\( Val_{total} \) is the total failure cost, \( Val_{i} \) is the failure cost in unit time, \( m \) is the total number of failure nodes, and \( t_{i} \) is the failure time. Under the same type of communication nodes, the longer the failure time is, the greater the failure cost. Therefore, the upper target can be equivalent to shortening the repair time as much as possible under the premise of priority restoration of important value nodes. Then, the solution of the two-layer optimization problem can be converted into solving the shortest repair time under the rules. The optimal solution can be acquired quickly through the shortest path search algorithm [13], avoiding problems such as a local optimal solution [14] of the two-layer optimization model.

The shortest repair time in this paper is determined by the team that spends the most time in the repair tasks assigned by the \( J \) repair teams:

\[ f_{i} = \max \{ (T_{r}, T_{L}, L, T_{j}) \} \]  

(2)

where \( T_{r} \) is the time that it takes repair team \( x \) to complete the allocated task and \( J \) is the number of repair teams.

With mobile base stations and emergency communication vehicles, the objective function is updated to:

\[ f_{i} = \max \{ \max(T_{r}, T_{L}, L), \max(T_{r}, T_{L}, L), \max(T_{r}, T_{L}, L) \} \]  

(3)

where \( K \) is the number of mobile base station repair teams and \( L \) is the number of emergency communication vehicles.

The constraints are as follows:

1. Each fault communication node can only be assigned and must be assigned to a repair team, and \( x_{jk} \) has a value of 1 when the node is assigned to any repair team.

\[ \sum_{x=1}^{J} x_{jk} = 1 \]  

(4)

2. At least one of the fibers connected to each distribution network communication node is normal, where \( l_{ij} \) is fiber \( j \) of communication node ‘\( i \)’. If the fiber is good, it takes the value 1; otherwise, it takes the value 0. \( P \) is the total number of fibers connected to the communication node.

\[ \sum_{j=1}^{P} l_{ij} \geq 1 \]  

(5)
(3) Any repaired communication node can be connected to a communication intermediate node via fiber optic. \( x_2 \) is a node that has resumed communication, and \( l_2 \) is the fiber between any failed node and the recovery node, where the fiber has a normal value of 1 and a break value of 0.

\[
\exists x_i, l_{ij} \sum_{k=1}^{f} x_{ik} = 1
\]

(6)

5. Experimental results

Take a practical topology in Zhangzhou as an example, the distribution network communication nodes correspond to power nodes one by one. The topological damage and resource distribution information of the communication system are obtained by the space-time mesh fusion method. Nodes 9, 12, 13, 15, 50, 51 are lifeline load. It is assumed that the repair times of a mobile base station, communication intermediate node and normal communication node are 40 min, 30 min and 20 min, respectively. For a unit distance, the fiber optic repair, emergency communication vehicles and repair teams travel 15 min, 10 min and 5 min, respectively; the value of a communication node corresponding to a lifeline load is 10; the value of a communication intermediate node is 5; and the value of a normal communication node is 1. There is one repair team for mobile base stations and two repair teams for fiber optics. The prediction of the fault position guides the allocation of emergency repair resources. In the absence of wireless communication, the teams repair nearby communication fault nodes. Figure 2 shows that the positions of repair teams affect the repair time and failure cost of the communication system after an extreme disaster. The closer a repair team is to a lifeline load node, the lower the cost caused by failure of the communication system. The closer a repair team is to a communication intermediate node, the shorter the repair time, and it is unfavorable to place a repair team at a nonfaulty node. Therefore, it is very important to predict the fault position of the distribution network communication system, and the accuracy of the prediction directly affects the allocation of emergency repair resources and the repair speed.

![Figure 2. Repair effects under different resource allocations](image)

If the existing repair resources and resource allocations are determined, whether the rules mentioned in this paper are applied, the corresponding repair time and failure cost of each method are shown in table 1.

Table 1. Repair effects corresponding to whether the rules are followed.

|                      | Only fiber optic | With mobile base station | With vehicle |
|----------------------|------------------|--------------------------|--------------|
| Not following the rules | Time/min | 472             | 352           | 274           |
|                      | Cost/Val/*t\_i | 32664              | 28643         | 20292         |
| Following the rules  | Time/min       | 499             | 471           | 402           |
|                      | Cost/Val/*t\_i | 14513              | 13911         | 8236          |

Even if the repair of a mobile base station restores some communication functions to some communication nodes corresponding to lifeline loads, the station can only transmit state information and cannot accept the control center signal. Therefore, this approach does not meet the requirements of emergency communication because these types of nodes should be repaired by fiber optic repair.
Table 1 shows that, although the repair time increases with the rules, the overall failure cost decreases significantly by close to 60%, which is in accordance with the repair requirements of the communication system after extreme disasters.

To show the comprehensiveness and rationality of the repair rules proposed in this paper, with the aim of guiding the repair work of the distribution network communication system after extreme disasters, quantitative discussion on the repair effects of only following some of the rules is conducted, and the results are shown in Table 2.

**Table 2.** Repair effects corresponding to different rules.

| Rules | Time/min | Cost/Val/\*t_i |
|-------|----------|----------------|
| None  | 272      | 20292          |
| 1     | 442      | 10224          |
| 1&2   | 436      | 10021          |
| 1&3   | 414      | 8432           |
| 1&2&3 | 402      | 8236           |

Table 2 shows that the rules can not only reduce the repair time but also reduce the failure cost. Combining the results of Tables 1 and 2, it can be seen that the first rule is strongly related to the failure cost, so the first rule is most important in terms of the failure cost.

In summary, the repair rules in this paper are effective, comprehensive and reasonable. By following the rules, the optimal repair plan of the case study is shown in Figure 3.

![Figure 3. Optimal repair scheme for the communication system after an extreme disaster](image)

**Figure 3.** Optimal repair scheme for the communication system after an extreme disaster

### 6. Conclusion

This paper mainly studies the optimization of the recovery strategy of a distribution network communication system under extreme disasters and considers the combination of fiber optics, mobile base stations and emergency communication vehicles. The following conclusions can be drawn:

1. The repair effects of the distribution network communication system after an extreme disaster are not only related to the repair strategy after the disaster but also affected by the allocation of emergency resources before the disaster and the speed of fault correction after the disaster. The coordination of wireless communication and fiber optic repair can optimize the repair effects of the distribution network communication system.

2. After an extreme disaster, once the communication system fails on a large scale, priority is given to fiber optic repair of the communication nodes corresponding to lifeline loads, the remaining nodes are given priority to restore communication through a mobile base station, and an emergency communication vehicle is given priority to restore the communication intermediate nodes.
The communication system restoration of the distribution network and power recovery complement each other. This paper focuses only on the communication nodes corresponding to lifeline loads and does not fully consider the coupling relationship between the distribution network communication system and power system. This is the research work that needs to be carried out in the future.

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