Research on power-communication coordination recovery strategy based on grid dividing after extreme disasters

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Abstract. Extreme natural disasters will cause great damage to the power and communication systems of the distribution network. During the restoration process of the distribution network, the power and communication systems interact and restrict each other. The coordination of the two can make the distribution network restore effectively and quickly. To improve the recovery speed and efficiency of the distribution network after disasters, power-communication coordination recovery strategies based on gridding method after disasters are proposed. Firstly, according to the corresponding relationship between mobile base stations and power nodes, multi-level grids of distribution networks are divided, and power-communication coordinated recovery models of distribution networks are respectively established aiming at short rush repair time and small power outage loss. On this basis, a coordinated recovery strategy of power-communication is proposed in combination with the gridding method. Finally, the IEEE33-node distribution network system is taken as an example to verify the necessity of the gridding method and coordinated power-communication recovery and the effectiveness of the proposed method.

1. Introduction

In recent years, the frequent occurrence of extreme disasters has increased the risk of power outages in the distribution network. With the development of communication systems, a variety of services such as production, control, and management have been grown rapidly, and the dependence of the distribution network on it has continued to increase [1-2]. Large-scale failures of power and communication systems occur after extreme disasters. Generally, the restoration of power precedes the restoration of communication systems. There is a lack of coordination between the two, and the coordination between the two may lead to more efficient and rapid recovery.

At present, existing related research usually repairs power failures in the order of user importance from the perspective of network reconstruction and fault recovery. Relevant experts have proposed a dynamic reconfiguration method of the distribution network to minimize network loss [3-4]; Past studies have shown that the restoration process of the distribution network system can be equivalent to two stages of grid reconstruction and failure recovery [5-8]. The research on the repair and recovery of the distribution network has not yet taken into account the impact of communication failures. In July 2016, the typhoon “Nibert” caused a total of 2784 communication base stations to be withdrawn from service in Fujian, communication in many areas was interrupted, and dispatching automation failed, the command center could not obtain the distribution network fault information in time, which seriously delayed the recovery and restoration of the distribution network [9]. In previous studies, relevant experts have established the public information model and topological structure of the...
distribution network communication system based on the characteristics and application requirements of my country’s power communication system [10]. However, there is no research on the coordinated recovery of power and communication failures in the distribution network after a disaster.

In the process of recovery and restoration of the distribution network, due to the lack of accurate division of the distribution network system and consideration of the micro-weather and topography of the area. This will make the data in the emergency recovery process redundant, and the established distribution network emergency repair recovery model is too complicated [11]. The gridding method can simplify the model utilizing grid discretization, thereby reducing the difficulty of solving [12]. To coordinate and adapt to the current situation of distribution network planning, references [13] adds a time dimension based on a geographic grid and fuses multi-source information of the distribution network to realize early warning of transmission line faults in the whole process of disasters. Relevant experts have proposed a method for predicting transmission line failures with multi-factor corrections in the grid [14]. However, in the extreme post-disaster repair of distribution networks, the application of grid technology is relatively small.

This paper proposes a grid-based strategy for the coordinated restoration of power and communication in the distribution network after extreme disasters. First, the multi-level grid division method of the distribution network is introduced, and a power-communication coordination recovery model for the distribution network is established with the goals of repair time and power loss; Secondly, a decoupling method for the power-communication coordination restoration problem of the distribution network is proposed to determine the power-communication coordination restoration strategy for the distribution network based on grid partitioning; Finally, the IEEE33 node distribution network system is taken as an example to verify the effectiveness of the proposed method.

2. Power-communication gridding modeling method for distribution network

2.1. Distribution network power-communication system structure

The structure of the distribution network power-communication system is shown in Figure 1. The communication nodes of the distribution network correspond to the power nodes one-to-one [15]. The optical fiber lines are the same as the power lines. A cluster head node is selected in a certain area to connect to the communication contact node. The distribution network communication methods mainly include optical fiber communication and wireless communication. Generally speaking, the distribution automation business with remote control function prefers the private network communication method. Feeder that rely on communication for automatic fault isolation should use optical fiber communication methods, information data collection, etc. Business can be transmitted through the public network. In summary, businesses with lower real-time requirements and lower safety factors such as power failure information monitoring of distribution networks after extreme disasters can be transmitted through optical fibers or public networks, but to control the reliability and real-time nature of the business, the dispatching automation operation instruction of the distribution network gives priority to optical fiber communication [16-17].

![Figure 1. Power-communication system structure of distribution network.](image-url)
2.2. Distribution network power-communication grid modeling

Traditional gridding methods mostly use the coordinates as the standard to establish a 3km*3km or 5km*5km geographic grid [18] and map the power joints and mobile base stations to the corresponding grids. But considering the base station and power joint correspondence, using this modeling method may make the power joints corresponding to the same base station distributed in different grids, increasing the complexity of emergency repair of the distribution network after the disaster. The power-communication grid in this paper uses the command center as the coordinates to establish an R1 level grid, named R (a), a is the number corresponding to the command center. In grid R (a), the base station is used to establish R2 as the coordinates, named R(a,b), b is the number of mobile base station in grid R(a), and divide grid R(a,b) into R(a,b,1) and R(a,b,2), the former corresponds to the mobile base station, and the latter corresponds to the power network; In the grid R (a, b, 2), the R3 level grid is established with the power nodes as the coordinates, named R (a, b, 2, c), c is the number of the power node in the grid R(a,b,2). Taking an R2 grid as an example, the division method and naming method are shown in Figure 2.

![Figure 2. Division and naming methods of R2 level grid.](image)

3. A bi-level optimization model for power and communication restoration of distribution network

3.1. The power-side fault recovery model of distribution network

Power-side recovery of the distribution network aims to minimize the economic loss caused by the faulty equipment and the shortest overall repair time, that is:

$$f_1 = \sum_{i=1}^{n} t_i w_i L_i$$

(1)

$$f_2 = \max \{\min T_1, \min T_2, \cdots, \min T_S\}$$

(2)

In the formula: $f_1$ and $f_2$ are the economic loss of power distribution system and the shortest repair time, $n$ is the number of failure points of the distribution network, $t_i$ is the total power failure time of failure point $i$, $w_i$ is the load level of failure point $i$, and $L_i$ is the load capacity, $\min T_i$ is the minimum time for repair team $i$ to complete the assigned task, and $S$ is the number of the repair team.

Power-side fault recovery mainly includes the following constraints.

1) Each power failure point of the distribution network can only be assigned and must be assigned to a repair team:

$$\sum_{k=1}^{M} x_{ik} = 1 \quad i = 1, 2, \cdots, n$$

(3)

$$\alpha < S$$

(4)

In the formula: $x_{ik}$ indicates whether the fault point $i$ is assigned to the repair team $k$. A value of 1 represents allocation and a value of 0 represents unassigned. $\alpha$ is the number of breakdowns for repairs.
2) Upstream node repairs are preceded by downstream nodes. If the upstream node fails, the power cannot be restored even after the downstream node is repaired. If the downstream faulted node has distributed power or is connected to other lines through a contact switch, the downstream node can be regarded as an upstream node.

\[ R_{t_i} \leq R_{t_j} \]  

Where \( R_{t_i} \) is the outage time of the upstream node \( i \), and \( R_{t_j} \) is the outage time of the downstream node \( j \).

3.2. The failure recovery model of communication side of distribution network

The fault recovery of the communication side of the distribution network is mainly considered from two aspects: firstly, the restoration of the optical fiber communication network enables the automation of the distribution switch of the distribution network, and by the way of the distribution network reconfiguration for quickly restores the load of the non-faulty area; Secondly, the communication network can accurately monitor the faults on the power side in real-time and guide the formulation of a power recovery plan for the distribution network after the disaster. The fault recovery of the communication side of the distribution network is divided into two methods: optical fiber communication network recovery [19] and mobile communication network [20-21], among which the corresponding goal of optical fiber communication network restoration is to maximize the load recovery of non-faulty sections, and the corresponding goal of mobile communication network restoration is to maximize the monitoring of power load.

1) The objective function of optical fiber communication network recovery is:

\[ f_3 = \sum_{i=1}^{N-n} w_i P_{L_i} \]  

The equality constraints are:

\[ P_{L_i} + \sum_{j \in N} x_{ij} P_{L_j} = P_{G_i} \]  

\[ Q_{L_i} + \sum_{j \in N} x_{ij} Q_{L_j} = Q_{G_i} \]  

\[ x_{ij} \in \{ 0, 1 \} \]  

\[ P_u = |P_{G_i} - P_{G_j}| \]

The inequality constraints are:

\[ L_{ij} \leq P_{ij} \leq U_{ij} \]  

\[ L_{G_i} \leq \Delta P_{G_i} \leq U_{G_i} \]

In the formula: \( f_3 \) is the total load of the non-faulty area that can be recovered through network frame reconstruction, \( N \) is the total number of nodes in the distribution network system, \( P_{L_i} \) and \( Q_{L_i} \) are the active power and reactive power consumed by node \( i \), and \( P_{G_i} \) and \( Q_{G_i} \) are nodes active power and reactive power injected by \( i \) power supply, \( x_{ij} \) is the line state variable, the normal value of the line is 1, the fault value is 0, \( P_u \) is the flow of line \( i-j \), and \( L_{G_i} \) and \( U_{G_i} \) are the lower and upper bounds of line \( i-j \) flow, respectively. \( L_{G_i} \) and \( U_{G_i} \) are the adjustable lower and upper bounds of the power node \( i \) respectively. \( \Delta P_{G_i} \) is the adjustment amounts of the power node \( i \).

2) The objective function of mobile communication network recovery is

\[ f_5 = \sum_{k=1}^{n} \frac{R_{k}}{N} \]

\[ \sum_{k=1}^{n} \frac{\text{Load}_{\text{Grid}(i,k)} \times a_3}{\text{Load}_{\text{sum}}} \]  

Restrictions:
\[ g_{ik} = \begin{cases} 1, & \text{Node } i \text{ is covered} \\ 0, & \text{otherwise} \end{cases} \quad (15) \]

\[ \text{Load}_{\text{Grid}}(a,b) = \sum_{i=1}^{\text{num}} w_i \cdot P_{li} \quad (16) \]

\[ \text{Load}_{\text{sum}} = \sum_{i=1}^{N} \omega_i \cdot P_{li} \quad (17) \]

In the formula: \( f_4 \) is the coverage rate, that is, the ratio of the number of nodes covered by the base station to the total number of nodes. \( f_5 \) is the monitorable proportion of the electric load. \( A \) is the number of R1 grids, \( B \) is the number of R2 grids, \( \text{Load}_{\text{Grid}}(a,b) \) is the amount of load to restore the R2 grid \((a, b)\), \( \text{Load}_{\text{sum}} \) is the total load that has been monitored, and \( g_{ik} \) is the power node \( i \) is covered by base station \( k \). The value of coverage is 1, the value of uncovered is 0, \( \text{num} \) is the number of power nodes corresponding to the grid \((a, b)\).

4. Power-communication coordination recovery strategy based on gridding method

Using the grid method, on the one hand, is conducive to solving the complex model of distribution network power-communication coordination recovery, on the other hand, it prevents the emergency communication recovery time of the distribution network system from being too long, which affects the speed of repairing the distribution network after disaster. To avoid long-term power loss in important load areas, the grid method is combined with the power-communication coordination recovery theory, as shown in Figure 3, which is a grid-based power grid-communication coordination recovery method process.

![Figure 3. Coordinated recovery process of distribution network based on grid methods.](image)

Taking the shortest recovery time as an example, and taking an R1-level grid as an example, the steps of generating a power-communication coordinated recovery plan are as follows:
1) Enter the state of the distribution network system and the status of the contact switch after the b-1th grid is restored;
2) Calculate the repair time time1 through the power side fault recovery in the b-th grid;
3) Calculate the repair time time2 to restore communication and then restore power in the b-th grid;
4) If time1 < time2, the scheme of step 2) is selected in the grid; if time1 > time2, the scheme of step 3) is selected in the grid, and the repair time is recorded as t(b);
5) Save and output the disaster recovery plan of the b-th grid, and count the recovery time of the b-th grid into the total time, and get the end time of the b-th grid t_b = t_b-1 + t(b);
6) If all loads of the grid are fully restored, the power-communication coordination recovery plan of the distribution network system after the disaster is output, otherwise, the load loss value of B-1 R2 grids is updated, and let b = b+1, jump to step 1), start the next recovery scenario calculation.

Among them:

\[
\text{time1} = \sum_{i=1}^{\text{num_good}} t_i + \sum_{j=1}^{\text{num_bad}} t_j \quad (18)
\]

\[
\text{time2} = t_{\text{com}} + t_{\text{elec}} \quad (19)
\]

In the formula: \( \text{num_good} \) is the number of non-faulty power nodes in grid b, \( \text{num_bad} \) is the number of faulty nodes in grid b, \( t_i \) is the time for the repair team to visit the non-failure node, \( t_j \) is the time for the repair team to repair the faulty node, and \( t_{\text{com}} \) is Time for repairing grid b communication failure. \( t_{\text{elec}} \) is the time to repair all power failures in grid b under normal communication conditions.

### 5. Case study

#### 5.1. Study scenario

This article takes the modified IEEE33 node distribution network system as an example, as shown in Figure 4, which is the failure scenario of the R1 level grid of the distribution network system after an extreme disaster. Table 1 is the node load and corresponding level, assuming each R1 there is a repair team in the grid, the corresponding grid number is R (1,2,2,1), the inspection time of a single non-faulted node is 5min, the distance between any two points is deterministic, and the movement time is 5min. The emergency repair time of each mobile base station (including a series of components such as steel pipe towers, antennas, feeders, and base station units in the area) is 15 minutes, and the emergency switch repair time of the contact switch FTU is 10 minutes, the repair time of power node failure is shown in Table 2.

| nodes | Load / level | node | Load / level | node | Load / level |
|-------|--------------|------|--------------|------|--------------|
| 1     | 124kW/1      | 12   | 65kW/2       | 23   | 65kW/2       |
| 2     | 78kW/2       | 13   | 60kW/2       | 24   | 70kW/1       |
| 3     | 55kW/2       | 14   | 56kW/2       | 25   | 52kW/5       |
| 4     | 53kW/1       | 15   | 70kW/5       | 26   | 48kW/3       |
| 5     | 28kW/3       | 16   | 80kW/2       | 27   | 45kW/6       |
| 6     | 80kW/3       | 17   | 36kW/1       | 28   | 61kW/2       |
| 7     | 70kW/4       | 18   | 58kW/6       | 29   | 50kW/3       |
| 8     | 70kW/5       | 19   | 50kW/1       | 30   | 29kW/1       |
| 9     | 62kW/6       | 20   | 52kW/2       | 31   | 18kW/1       |
| 10    | 52kW/6       | 21   | 78kW/2       | 32   | 30kW/2       |
| 11    | 45kW/10      | 22   | 64kW/2       | 33   | 32kW/2       |
Table 2. Fault level and rush repair time.

| Failure level | node           | Repair time |
|---------------|----------------|-------------|
| First         | 3, 10, 18, 30, 31 | 20min       |
| Secondary     | 4, 6, 16, 23, 32 | 30min       |
| Third         | 13, 22, 24, 28  | 40min       |

5.2. Analysis of recovery goals of distribution network after disaster

After the occurrence of extreme disasters, this paper considered five post-disaster recovery solutions for the distribution network. The first solution is the recovery solution without communication failure, and the other four are the recovery solution under communication failure. The second case is the repair of pure power failure, scheme 3 is a power-communication coordination restoration scheme based on partial communication priority restoration, scheme 4 is a grid-only restoration scheme, scheme 5 is a grid-based distribution network power-communication coordination restoration scheme.

Regarding the recovery goals of the distribution network system after extreme disasters, this paper mainly considers the two aspects of the repair time and the power outage loss. Figure 5 shows the rush repair duration and power outage loss of the distribution network under each repair plan, and the power outage loss is the sum of the 33 node losses. In each column, each color represents the coincidence loss of each node. It can be seen from the comparison with scheme 1 that the failure of the distribution network communication system greatly reduces the emergency repair speed of the distribution network after the disaster and increases the power outage loss of the distribution network.
Figure 5. Power loss and recovery time of distribution network under five schemes after disasters.

From the perspective of emergency repair time: the distribution network power-communication coordination recovery method and grid-based power-communication coordination recovery method based on partial communication priority restoration can effectively shorten the emergency repair time of the distribution network. Since the recovery of communication failures is conducive to the monitoring and location of power failures and guides the precise repair of power failures after disasters, and it is possible to avoid the repair of catastrophic power failures through grid reconstruction, therefore, the coordinated recovery of power-communications can be accelerated after an extreme disaster the efficiency of the emergency repair of the distribution network after the disaster.

Considering from the loss of power outages: the grid theory is used to restore each grid in order from high to low load value after extreme disasters, to avoid long-term power outages of important loads in the distribution network, which can effectively reduce the power loss of the distribution network after extreme disasters. Although the single use of the grid method can effectively reduce the loss of the distribution network after the disaster, the time for the distribution network system to restore the initial state is too long, and it is better to consider the coordinated recovery of power communication within the grid.

6. Conclusions
In this paper, from the perspective of the emergency repair time of the distribution network and the loss of power outage after extreme disasters, a grid-based coordinated power-communication recovery strategy for the distribution network is proposed, which effectively improves the distribution network’s power distribution in the event of a large-scale failure of the distribution network. Resilience, the results of this study show: 1) Considering the coordinated recovery of power-communications after an extreme disaster can speed up the repair efficiency of the distribution network after the disaster, applying the gridding method to repair the distribution network after the disaster can effectively reduce the power outage losses of the distribution network; 2) The combination of gridding method and power-communication coordination recovery theory is applied to emergency repair of distribution network after disaster, which can shorten the length of emergency repair of distribution network and reduce the loss of power outage.

This paper considers the grid-based distribution network power-communication coordination recovery strategy, which is helpful to guide the emergency repair of the distribution network system after extreme disasters. The combination with the distribution network and road network after the actual disaster and consider the impact of critical infrastructure on emergency repair and recovery strategies under various extreme disaster conditions will be the next research direction of this paper.

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