Integrated Emergency Response for Distribution Network Maintenance and Recovery After Natural Disasters

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Abstract. This paper proposes a two-stage method of outage management for distribution network maintenance and recovery after natural disasters. In the first stage, all the fault points are clustered based on their distances from the depots and the availability of repair resources. The second stage solves the repair and restoration problems based on clustering results. With the aim of maximizing the picked-up loads in the shortest time, the routing schedule of the fleet is finally obtained. A mixed-integer linear programming model is developed to solve the co-optimization problem, considering the distribution network operation constraints and the constraints of routing repair crews, which are scheduled based on the resource availability, traveling time and maintenance time. The proposed method is verified on the modified IEEE 34-bus distribution system with multiple damages.

1. Introduction

With the frequent occurrence of extreme weather and natural disasters in recent years, how to improve the emergency management level of distribution network outage under extreme conditions has become an urgent problem to be solved[1]. At present, after the power failure of distribution networks, most of them rely on the existing equipment and power supply in the power grid to restore, and there is a lack of optimizing the use of external equipment, personnel and other emergency resources. However, after the typhoon and flood disaster, there may be many lines broken, tower down, power failure and other situations, which require a large number of standby materials to replace the damaged equipment[2]. Reserve stocks are relatively concentrated in a few warehouses, while maintenance sites, equipment and personnel required for maintenance are relatively dispersed. In order to speed up the recovery process and shorten the recovery time of power supply, it is necessary to optimize the allocation of the emergency maintenance resources that are urgently needed by the power grid, realize the coordination with the goal of power supply restoration, and restore the distribution network to normal operation as soon as possible[3].

The allocation of power emergency resources mainly includes the acquisition of resources and the optimal scheduling of resources. The scheduling of resources can be specific to the scheduling problem of maintenance teams. Relevant personnel visit the fault points in turn with the resources needed for fault maintenance to complete the allocation of resources. Therefore, the scheduling problem of maintenance teams can be modeled as Vehicle Routing Problem (VRP), which is an integer
combinatorial optimization problem aiming at finding the optimal path of the vehicle fleet under certain constraints[4]. And resources reserves is the precondition of can be configured, but its own characteristics in electric power lead to its limited storage capacity, often a single area of emergency resources reserve is insufficient to deal with extreme weather and natural disasters caused by the power demand of resources. Therefore, it is necessary to consider the coordinated scheduling of resources in multiple regions[5].

The research on the combination of power supply restoration and resource allocation in distribution network is relatively complex, most of them are carried out separately without considering the mutual influence between them. Ref. [6] proposes a layered outage management method, which can identify and allocate the main resources required by the outage. However, this multi-micro-grid management method cannot be fully applied to the distribution network. Ref. [7] adopts the queuing theory and the theory of random point process to model the maintenance process and optimize the maintenance team scheduling to reduce the outage time. Ref. [8] studies the emergency resource scheduling scheme in the case of large area power failure with the objective of enhancing system operation stability and reducing power failure loss. In Ref. [9], a multi-target bacterial population medicinal algorithm was adopted to establish a joint optimization model of fault maintenance and recovery in order to minimize economic losses and the time to complete fault maintenance, but no specific research was conducted on the contents of recovery. Although Ref. [10] has also proposed a joint optimization model of multi-fault repair and power supply restoration, the modeling of the optimization problem of repair sequence is relatively simple. Ref. [11] uses the dynamic programming principle for distribution network fault repair and optimizes power supply recovery, and solving process is relatively complicated and no maintenance path planning is given.

Integrated emergency response should be a problem of coordinating and optimizing load power supply recovery and fault maintenance. On the one hand, they are independent of each other, and on the other hand, they affect and depend on each other. Only by alternating and parallel power supply recovery and fault maintenance can we finally achieve the goal of maximizing load recovery in the shortest time. In this paper, the mixed integer linear programming model (MILP) is established to combine maintenance and recovery, and finally achieve the goal of maximizing load recovery in the shortest time at the same time.

2. Model of maintenance

The resource allocation problem of equipment and personnel is transferred to the maintenance process, which is transformed into the planning problem of the maintenance route. Different from the traditional vehicle routing problem (VRP), not only the amount of resources required by each fault point but also the repair time of it needs to be considered. Therefore, the planning of the maintenance route is handled as follows:

Each repair crew departs from the warehouse and accesses the fault point with the number of resources obtained from the warehouse that do not exceed its own load, and finally returns to the warehouse, assuming that there is a total of M fault points. Set the resource reserve of the warehouse to $R_c$, the resource that each maintenance team can carry is $R_x$ and the resource needed by fault point $m$ is $R_m$. The travel time between the fault point $m$ and $m+1$ is $T_{m,m+1}^{tr}$, the repair time required for each fault point $m$ is $T_{m}^{rp}$, the time when the repair crew reaches the fault point of failure is $T_{m}^{A}$. $X_{m,m+1}$ is the path between $m$ and $m+1$, if the repair crew walks from $m$ to $m+1$, then $X_{m,m+1}$ is assigned to 1. The maintenance process is shown in figure 1.
Figure 1. Description of the repair process.

The resources carried by each repair crew should meet the following constraint:

\[ \sum_{m=1}^{M} R_m \leq R_x \leq R_c \]  

The time when the repair crew reaches the fault point \( m+1 \) should equal to the time when the repair crew reaches the fault point \( m \) plus the repair time of the fault \( m \) and the travel time of \( m \) to \( m+1 \), i.e.

\[ T^A_{m+1} = T^A_m + T^{rp}_m + T^{tr}_{m,m+1} \]  

Once a fault point is repaired, the repair crew moves to the next fault point. i.e.

\[ \sum_{m \in V} X_{m,m+1} + \sum_{m \in V} X_{m+1,M} = 1 \]  

However, the amount of resources that each warehouse can reserve is limited, and the resources carried by each repair crew are limited as well. Under normal circumstances, the resources that a repair crew can carry are not enough to repair all the fault points. Therefore, we depart all fault points into different clusters first. On the one hand, it can ensure that the number of resources carried by the repair team can meet the requirements of all fault points in the cluster, on the other hand, dividing the single VRP into several small VRPs can also reduce the computational complexity of subsequent optimization.

The fault points are departed into \( S \) clusters, each cluster is equipped with a warehouse \( n \) \((n=1, 2, \ldots, S)\) and a repair team. The clustering problem is established into an integer linear programming model, and the input of the model is the distance from the fault point to each warehouse, i.e. \( D(n,m) \). A 0-1 variable is used to represent the cluster of fault points, if the fault point \( m \) belongs to cluster \( n \), then \( s_{n,m} = 1 \). The clustering is shown in figure 2, for each fault \( m \), it should belong to the nearest warehouse. However, it is also necessary to ensure that the resource of the warehouse should be greater than or equal to the total resource demand of all the fault points classified in the cluster. The objective of the clustering problem is as follows:

\[ \min_{s} \sum_{n} \sum_{m} D(n,m)s_{n,m} \]  

Figure 2. Clustering of fault points.
3. Coordinated optimization of repair and recovery

The coordinated optimization model mainly solves two problems. The first is to restore the distribution network load maximally with the available resources, and the second is to allocate the equipment and personnel resources in the shortest time, that is, to solve the scheduling problem consist of warehouses, resources, repair crew, and fault points.

A mixed integer linear programming model is established to maximize the recovered load in the shortest time, the objective of which is:

$$\max \alpha \sum_{i} \sum_{j} a_{i} k_{i,j} p_{i}^{j} - \alpha \sum_{m} a_{m} b_{m,t}$$

(5)

Mixed integer linear programming assigns a weight coefficient to each of the two targets, because the main goal of emergency recovery is to the load restoration, we set $\alpha$ as the weight coefficient of the load, which can ensure that the load with high priority is restored first; $p$ is the active power of the node; $k$ represents the state of the load, if the load has been restored, then $k=1$. $a_{m}$ is the weight of the fault point $m$, considering the radiation of the distribution network, if a fault is located on the main feeder, the value of $a_{m}$ is larger, so that the point where the fault has a large impact is restored early. $b$ is a 0-1 variable indicating whether the fault has been repaired. Linearized constraints is listed as follows:

$$\sum_{m}^{X_{m,m+1}} + \sum_{m}^{Y_{m,m+1}} \leq 1 \ \forall s$$

(6)

$$\sum_{m}^{X_{m,m}} - \sum_{m}^{Y_{m,m}} = 1 \ \forall s$$

(7)

$$\sum_{m}^{Y_{m,m}} = 1 \ \forall s$$

(8)

$$y_{m}^{s} = \sum_{m}^{X_{m,m+1}} \ \forall s$$

(9)

$$T_{m}^{a} + T_{m}^{b} + T_{m,m+1}^{a} - T_{m}^{a} \leq (1 - X_{m,m+1})M \ \forall s$$

(10)

$$\sum_{m}^{b_{m,t}} = 1 \ \forall s$$

(11)

$$\sum_{m}^{t_{b_{m,t}}} \geq T_{m}^{a} + T_{m}^{b} y_{m}^{s} \ \forall s$$

(12)

$$\sum_{m}^{t_{b_{m,t}}} \leq T_{m}^{a} + T_{m}^{b} y_{m}^{s} + 1 - \varepsilon \ \forall s$$

(13)

$$0 \leq T_{m}^{a} \leq y_{m}^{s} M \ \forall s$$

(14)

$$z_{m,t} \leq \sum_{t} b_{m,t} \ \forall s$$

(15)

$$u_{m,t} \leq z_{m,t} \ \forall s$$

(16)

Constraints (6)- (9) are about the maintenance route, (6)- (8) ensure that the faults will not be repaired repeatedly and (9) represents that if the fault $m$ has been repaired, $y$ is assigned to 1. Constraint (10) is the linearization of equation (2) with a big M method. Constraint (11) ensures that the faults will not be repaired repetitively. Constraints (12)- (13) are on the time when the faults are repaired. Constraint (14) using a big M method to make sure that if a fault has not been repaired, then the above constraints are invalid. Constraint (15) pledges that the fault that has been repaired should maintain in normal working condition for the next period of time. Constraint (16) represents the relationship between the maintenance and recovery. In addition, line current constraints, node voltage constraints, node recovery states, and radiated topology constraints during recovery are also considered as ref. [5].

4. Case study

The mixed integer linear programming model is numerically tested in the IEEE34 node power distribution system. The program is written using MATLAB R2014b, and CPLEX is called to solve the problem, assuming that locations of the fault points are known. As shown in figure 3, this paper takes
the IEEE 34-node power distribution test system provided in [12] as an example, assuming that this network has five fault lines (N1, N2, N3, N4, N5) and two warehouses with ten units of emergency resources. The load connected to node 33 is important, so there is a 150kW distributed power supply. Table 1 shows the repair time and maintenance resources required for each fault point. The maintenance path is shown in figure 4, the repair sequence of faults and nodes are respectively shown in table 2 & 3.

![IEEE34 node system with faults.](image1)

![Maintenance route planning results.](image2)

| Fault point | Repair time/(20 minutes step) | Repair resources |
|-------------|-------------------------------|-----------------|
| N1          | 2                             | 2               |
| N2          | 2                             | 3               |
| N3          | 3                             | 2               |
| N4          | 3                             | 4               |
| N5          | 2                             | 3               |

Table 2. Repair sequence.

| Time/(20 minutes step) | Fault points |
|------------------------|--------------|
| 1-4                    | /            |
| 5                      | N1, N3       |
| 6-8                    | /            |
| 9                      | N2           |
| 10                     | N5           |
| 11-14                  | /            |
| 15                     | N4           |
5. Conclusion
In this paper, the problem of integrated emergency response for distribution network maintenance and recovery after natural disasters is studied. The resource allocation problem is treated as VRP and a clustering method based on the fault points is proposed, which ensures that the maintenance teams in each cluster do not need to go back and forth to the warehouse to replenish resources, thus shortening the maintenance time. The coordination optimization model of emergency recovery and resource allocation of distribution network was established and optimized, and finally a single-objective mixed integer linear programming model was established to achieve the goal of maximizing load recovery in the shortest time. An example of an IEEE 34-node distribution network is given to demonstrate the superiority of the coordination optimization method in solving the emergency recovery problem.

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