Network Recovery for Large-Scale Failures in Smart Grid by Simulation

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Abstract. Large-scale natural disaster or malicious attacks could cause serious damage to the power communication network in smart grid. If the damaged network cannot be repaired timely, great threat will be brought to the secure and stable operation of power grid. Therefore, an importance-based recovery method for large-scale failure has been proposed in smart grid by simulation. Firstly, the link importance for the whole network is calculated according to the solution of the link importance for the services type and the importance of services type for the power communication network. Secondly, a fault recovery model with the sum of the importance of each fault link has been established to recover more important communication services under the condition of limited resources. Finally, we propose a heuristic algorithm to reduce the expenditure of time, and then compare the results of the model with the 0–1 integer programming method to verify the feasibility of the method. The experimental results show that the links which carry high-priority can get priority to be repaired in the paper, thus it ensures the safe and stable operation of power communication network.

Keywords: Network recovery · Smart grid · Large-scale failures · Simulation

1 Introduction

Communication network is the basis for guaranteeing the safe and stable operation of the smart grid. It is heavily depended to support the services of urgent protection and control in smart, especially in times of emergency. When the large-scale failure are caused by nature disaster, blackout, and malicious, huge economic losses and serious social impact will be brought, if the failure of network cannot be restored timely [1–3]. For example, in 2005, the serious accident of large-scale communication optical cable interruption in Central China Power Grid has caused the central China Network to be basically in a state of paralysis, which poses a great threat to the safety of the power grid. In the south of China, a large number of interconnected optical cables have been disrupted due to snow disaster, which has led to the split operation of the communication network and seriously affected the stable operation of the power system. After the large-scale failures of communication network in smart grid, it takes a large number of manpower, material, financial and other resources to restore the power, which results in the recovery of the power communication network after a large-scale failure cannot be fully expanded at the

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same time. Therefore, it is essential that repairing the damaged infrastructures of smart grid, at least to the point where mission-critical services can be supported [4].

There have been a lot of research on large-scale network failure recovery in telecommunication network. An iterative segmentation and deletion method has been proposed, which decomposes the problem of large-scale network recovery into sub problems and the set of network component has been obtained [5]. The importance assessment method for damaged network components has been proposed in [6], the network component is repaired according to their importance. In [7], a GSR heuristic algorithm for maximizing network traffic has been proposed, it combines multiple fault components randomly, and decreases the computation time by reducing the number of fault components. In [8], a fault probability detection method based on wave energy has been proposed, which can prevent and protect large-scale networks, improve the efficiency of uninterrupted transmission of data, and reduce the interruption time on a large-scale of network. A forward and backward-based heuristic algorithm has been proposed to solve the multi-stage network recovery after large-scale network failures [9]. In [10], superposition network technology has been used to calculate multiple routing configurations in advance to prevent simultaneous network failures, thereby improving the network tolerance performance of disaster.

However, the communication network is different from the telecommunication network [11]. There are multiple services. Each service has different delay and reliability requirement, and importance of each service is also different smart grid. Therefore, after the large-scale failures of communication network, how to repair the important service quickly and ensure the reliable operation of power system is particularly important. In the paper, an importance-based recovery method for large-scale failure has been proposed in smart grid by simulation. In the method, the link importance is calculate by K shortest path algorithm [12], the heuristic algorithm, considering the characteristics of power communication network, has been proposed to solve the problem. In the algorithm, we consider the link importance and the priority of communication network. Thus, the critical services in power communication network is firstly and quickly repaired.

2 The Characteristics of Communication Network in Smart Grid

According to the relevant regulations of the security protection management system in smart grid,the services can be divided into four major categories and safety zones, such as operation control services(Safe Area I), operation information services(Safe Area II), management information services(Safe Area III), and management Office services(Safe Area IV). The detailed information about the relative importance of each service is introducing in [13].

A method for calculating the importance of service is also given in [13]. Firstly, the relative importance values of each service is calculated, and it is represented by a_i^{Sum}, as shown in Eq. (1). Secondly, a_i^{Sum} is normalized according to the Eq. (2). After the normalization, the minimum value of $\left(a_i^{Sum}\right)'$ may be 0, which means that the importance of the service is 0 and the service can be discarded. Obviously, it is unreasonable. Therefore, it needs to be mapped to the interval [X, 1] according to the Eq. (3). When the value of X is 0.1, the distance between the maximum and minimum of the importance for each service is 10. Finally, the values of the importance for each service are shown in Table 1.

$$a_i^{Sum} a_i^{Sum} = \sum_{j=1}^{6} a_{ij} \tag{1}$$

$$\left(a_i^{Sum}\right)' = \frac{a_i^{Sum} - \left(a_i^{Sum}\right)_{\min}}{\left(a_i^{Sum}\right)_{\max} - \left(a_i^{Sum}\right)_{\min}} \tag{2}$$

$$Q_i = \left(a_i^{Sum}\right)'(1 - X) + X \tag{3}$$

Table 1. The importance of power services in smart grid

Services	Importance	Services	Importance
550 kV Protective Relay	1.00	Video Conferencing	0.38
220 kV Protective Relay	0.95	Video Monitoring in Substation	0.34
Safety and Stability System	0.91	Protection Information Management	0.29
Wide-Area Measurement	0.86	Lightning Location Detection	0.29
Dispatching Automation	0.72	Administrative Telephone	0.19
Dispatching Telephone	0.57	Office Automation	0.10
Electric Energy Telemetering	0.53		

In order to simplify the analysis, 13 kinds of services can be divided into 5 types according to the approximation of importance and the characters of services. The importance of each type is the average of all services in this type, as shown in Table 2.

Table 2. The division of service types and related parameters

Type	Services	Importance of type/w^m	Transmission bandwidth/b_m
I	550 kV Protective Relay	0.98	2
	220 kV Protective Relay		
II	Safety and Stability System	0.91	2
III	Wide-Area Measurement	0.67	2
	Dispatching Automation;		
	Dispatching Telephone;		
	Electric Energy Measurement Telemetry		

(*continued*)

Table 2. (*continued*)

Type	Services	Importance of type/w^m	Transmission bandwidth/b_m
IV	Video Conferencing	0.33	2
	Video Monitoring in Substation		
	Protection Information Management		
	Lightning Location Detection		
V	Administrative Telephone	0.15	1
	Office Automation		

3 Recovery Strategy and Algorithm

3.1 Problem Description

Link importance is a standard to evaluate the performance of links to the network, and it is also the reference to allocate limited recovery resources for the damaged links. The damaged links with high importance has the priority to use the recovery resources and can be repaired firstly.

There are many services in the communication network of smart grid. The services can be divided into different types which represent by M according their characteristics. If we calculate the paths for each service of one type with the K shortest paths algorithm, the ratio which the frequency of the K shortest paths traverses link (i, j) and the frequency of the K shortest paths traverses all kinks reflects the importance of link (i, j) for this type. We define it as Eq. (4).

$$\pi_{ij}^{m} = \frac{F_{(\mathrm{i},j)}^{m}}{F^{m}} \tag{4}$$

As shown in Eq. (1), if we calculate the K shortest paths for each service in the m-th type, $F_{(\mathrm{i},j)}^{m}$ can represent the frequency that K shortest paths traverse the link (i, j) and F^m can represent the number of all links that K shortest paths traverses. However, different types of service have different weight for the network which represent by w^m. The importance of the same link may different from different types. So, we use q_{ij}^{m} to describe the importance of the link (i, j) in the *m-th* type for the network, as shown in Eq. (5).

$$q_{ij}^{m} = w^{m}\pi_{ij}^{m} \tag{5}$$

Considering the characteristics of the services in the communication network of smart grid, the recovery result is evaluated by $f(Q)$, which is the sum of the link importance values of the repaired links. We define it as the objective function in Eq. (6).

The flow balance constraint is given by Eq. (7), where x_{ij}^{p} represents if the service p traverses link (i, j), going from node i to node j. If the service p traverses link (i, j), $x_{ij}^{p} = 1$; otherwise, $x_{ij}^{p} = 0$. The capacity constraint of each link is shown in Eq. (8), where B_{ij} represents the bandwidth of the link (i, j) before the large-scale failure and b_{ij} represents the bandwidth of the link (i, j) after large-scale failure in the network.

We assume that 1 unit of recovery resources is consumed in the link per kilometer, so the recovery resources which the damaged link (i, j) is to be consumed is introduced in Eq. (9), where d_{ij} represents the length of link (i, j).

Recovery resources are limited throughout the total recovery stages, so the constraint in Eq. (10) is to limit the resource, which is represented by R. If the damaged link (i, j) is repaired, $x_{ij} = 1$; otherwise, $x_{ij} = 0$. r_{ij} represents the resource of repairing the damaged link (i, j). Finally, Eq. (8) represent that a damaged link can be repaired only once throughout the recovery stages.

The network recovery problem can be formulated as follows:

Objective function:

$$\max f(Q) = \sum_{\mathrm{m}=1}^{M} \sum_{(i,j)\in\Lambda} x_{ij}\, q_{ij}^{m} \tag{6}$$

Subject to:

$$\sum_{\mathrm{(i,j)\in E}} x_{ij}^{p} - \sum_{\mathrm{(j,i)\in E}} x_{ji}^{p} = \begin{cases} 1 & i = p(\theta) \\ -1 & i = p(\theta) \\ 0 & others \end{cases} \tag{7}$$

$$\sum_{m=1}^{M} \sum_{p=1}^{P_m} b_m x_{ij}^{p} \le b_{ij} + (B_{ij} - b_{ij}) x_{ij} \tag{8}$$

$$r_{ij} = (B_{ij} - b_{ij}) d_{ij} \tag{9}$$

$$\sum_{m=1}^{M} \sum_{(i,j)\in\Lambda} x_{ij} r_{ij} \le R \tag{10}$$

$$\sum_{m=1}^{M} x_{ij} \le 1 \tag{11}$$

3.2 The Proposed Algorithm

The mathematical model described above is 0–1 programming, which is NP-hard. When the model is solved by searching, its computation time will increase exponentially as the number of damaged links increases [14]. Especially when the extent of failure is larger, it is extremely difficult to determine an appropriate recovery order within a practical time. Therefore, we propose a link importance-based heuristic algorithm as follows:

Firstly, the importance of each damaged link in different types is obtained according to the Eq. (4)–(5), and they are sorted in the descending order. Secondly, we repair the damaged links from the high priority type to the low priority type. Note that the damaged link which has been repaired in high priority of type, will not be repaired again in low priority of type. Finally, the objective value can be calculated according to the damaged links which has been selected to repair.

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Algorithm:
Input: The damaged links set of different types $L_m$, repaired links set $L$,
Divide all services into $M$ types and each type of services have the priority $m$, which 0 represent the highest priority.
Calculate $q_{ij}^{m}$ for all damaged links in different types of services, and sort them in descending order;
while $m \le M$ and $R \ge 0$ do
    while $L_m \ne \phi$ and $R \ge 0$ do
        Find the damaged links (i,j) with the maximum of $q_{ij}^{m}$;
        if $x_{ij} = 0$ then
            $R = R - r_{ij}$ and $x_{ij} = 1$;
            Move the link (i,j) from $L_m$ to L;
    m=m+1;
Calculate the objective function value according $L$;
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4 Computational Experiments

In this experiment, we use the network topology of the backbone transmission network of Guangdong province as Fig. 1, which consist of 14 nodes and 16 links. The number between nodes represent the distance of them (*KM*). Meanwhile, we assume that all links is partial damaged or damaged completely besides the link of (7, 8) and (6, 7). The capacity of links before failure and after failure are shown in Table 3, and the transmission rate in this experiment is 2×10^8 m/s. The distribution of different types services (s, d) in the network is shown in Table 4, where s represent the source and d represent the destination of the services.

In the experiment, we verify the performance of the proposed algorithm for the target values under the different resources. The resource for recovering the damaged network is {100, 200, 300, 400, 500, 600, 700, 800}, respectively. The results is shown

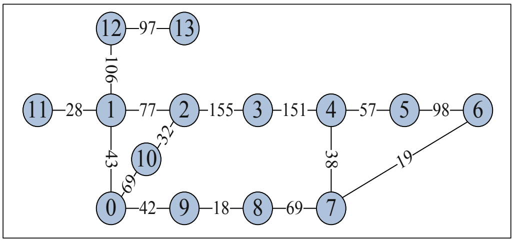


Fig. 1. The backbone transmission network topology of Guangdong Province

Table 3. The bandwidth of links before and after failure in network

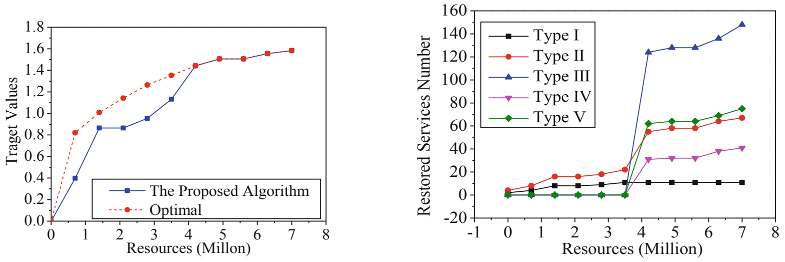
Links	The bandwidth before/after failure	Links	The bandwidth before/after failure
(0, 1)	10240/0	(2, 10)	10240/8000
(0, 9)	10240/0	(4, 5)	10240/10000
(0, 10)	10240/1000	(4, 7)	10240/8000
(1, 2)	10240/1000	(5, 6)	10240/10000
(1, 11)	10240/2000	(6, 7)	10240/10240
(1, 12)	10240/2000	(7, 8)	10240/10240
(2, 3)	10240/4000	(8, 9)	10240/0
(3, 4)	10240/4000	(12, 13)	10240/0

Table 4. The distribution of different services in network

Services (s, d)	Type × number	Services (s, d)	Type × number
(0, 1)	II × 5 + III × 20 + IV × 5 + V × 10	(1, 2)	I × 1 + II × 2
(0, 2)	II × 3 + III × 12 + IV × 3 + V × 6	(1, 11)	I × 1 + II × 2
(0, 3)	II × 2 + III × 8 + IV × 2 + V × 4	(2, 3)	I × 1 + II × 2
(0, 4)	II × 5 + III × 20 + IV × 5 + V × 10	(3, 4)	I × 1 + II × 2
(0, 5)	II × 2 + III × 8 + IV × 2 + V × 4	(3, 10)	I × 1 + II × 2
(0, 6)	II × 6 + III × 24 + IV × 6 + V × 12	(4, 5)	I × 1 + II × 2
(0, 7)	II × 3 + III × 12 + IV × 3 + V × 6	(4, 7)	I × 1 + II × 2
(0, 8)	II × 2 + III × 8 + IV × 2 + V × 4	(5, 6)	I × 1 + II × 2
(0, 9)	II × 2 + III × 8 + IV × 2 + V × 4	(6, 7)	I × 1 + II × 2
(0,10)	II × 2 + III × 8 + IV × 2 + V × 4	(7, 8)	I × 1 + II × 2
(0, 11)	II × 3 + III × 4 + IV × 1 + V × 2	(8, 9)	I × 1 + II × 2
(0, 12)	II × 4 + III × 8 + IV × 6 + V × 5	(13, 14)	II × 3 + III × 12 + IV × 3 + V × 6

in Fig. 2, where (a) is the comparison of target values with 0–1 programing and heuristic algorithm and (b) is the recovery result of different types of services.

It can be seen from the Fig. 2(a) that the gap between the optimal value and the value of the proposed algorithm is getting smaller with the increasing of resources. The



(a) (b)

Fig. 2. The result of network recovery under different resources

more the resources is, the better the performance of the proposed algorithm. Moreover, the target values of proposed algorithm is the same as the optimum when the resource is more than 4 million.

We can see from the Fig. 2(b) that the types of services which have high priority has been restored firstly when the resource is little. Meanwhile, the types of services which have low priority is restored gradually with the increasing of resource.

As discussed above, it can show that as the resources increase, the proposed algorithm can acquire the good recovery performance when the network have a large-scale failure. The gap between the proposed algorithm and the optimal value is much lower with the increasing of resource. Meanwhile, the types of services which have high priority can be restored firstly to ensure the safe operation of smart grid. Therefore, we can conclude that the proposed algorithm in this paper is suitable for the recovery of large-scale network failure.

5 Conclusion

When the smart grid has been destroyed by the large-scale failures, the objective of network recovery in smart grid is to restore the types of services which have high priority firstly. So, a subset of the damaged components is selected to repair after a large-scale failure with the limited recovery resources. We have formulated the problem as 0–1 programming model, which is NP-hard. A Link Importance-based heuristic algorithm has been proposed to solve the problem. Simulation experiments have shown that the heuristic algorithm provides a good solution. However, according to the experimental results, we can find that there is a gap between the heuristic algorithm and the optimal value. In the future work, a better combination optimization method should be found, so that the best recovery effect can be reached as soon as possible after the large-scale failure.

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