Multi-stage Network Recovery to Maximize the Observability of Smart Grids

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Abstract. Large-scale natural disaster or malicious attacks could cause serious damages to communication networks in smart grids. If the damaged network cannot be recovered timely, greater threat will be brought to the secure and stable operation of smart grids. However, network recovery will take a lot of time, and the recovery process will involve multiple stages due to the limited recovery resources. In this paper, we address the problem of network recovery by selecting partial damaged links to be repaired in every stage so as to maximize the number of survival services. We formulate the problem as 0–1 programming, and then propose a heuristic algorithm to solve the problem. Extensive simulations are carried out on some topologies, the number of services, and the number of stages. The simulation results demonstrate that the heuristic algorithm is time-efficient and near-optimal.

Keywords: Smart grids · Multiple-stage · Network recovery · Large-scale Failures

1 Introduction

Communication network is the infrastructure for suring the safe and stable operation of smart grids. It is heavily depends to support the services of urgent protection and control in smart grids, especially in times of emergency. When large-scale failures are caused by nature disaster, blackout, and malicious, huge economic losses and serious social impacts will be brought, if the failures cannot be restored timely. Therefore, it is essential to recover the damaged communication network of smart grids, at least to the point where mission-critical services can be supported.

Much research on network recovery has been reported in telecommunication networks, which can be classified into single-stage [1] and multi-stage recovery [2–4]. In telecommunication networks, the objective of network recovery is to maximize the traffic of the total network [5]. The problem of efficiently restoring sufficient resources in communication networks has been addressed; An iterative split and prune algorithm, which is a polynomial-time heuristic, has been proposed [6]. The importance assessment method for damaged network components has been proposed in [6], the network components ware repaired according to their importance. A multiple stages network recovery

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method was proposed in [7], and it can determine an appropriate recovery order of damaged network components and consider both prompt network service recovery and fair traffic recovery to meet traffic demand. The network recovery under uncertain knowledge of damages has been studied [8], and it was formulated as a mixed integer linear programming (MILP), which is NP-hard. An iterative stochastic recovery algorithm (ISR) has been proposed to recover the network in a progressive manner to satisfy the critical services.

However, communication networks of smart grids are different from telecommunication networks because they are mission-critical. In smart grids, the more services survive, the more components of power grids can be observed, and the more secure operation of smart grids can be guaranteed when large-scale failures occur. Therefore, the reliability requirement of communication networks is more complicated and important for smart grids. Most researches concentrate on network frameworks and multipath to improve network reliability against network failures. An end-to-end attack-resilient cyber-physical security framework for WAMPAC applications in power grids was introduced; and a defense-in-depth architecture has been described in [9]. An optimization-based restoration strategy was developed to coordinate the restoration actions between power grids and communication networks [10]. The problem was modelled as a mixed integer linear programming problem, with the objective of activating every node in both networks with the minimum number of activation/energization of branches. A self-healing phasor measurement unit (PMU) network has been investigated to exploit the features of dynamic and programmable configuration in a software-defined networking infrastructure to achieve resiliency against cyber-attacks [11].

In smart grids, much research has focused on network frameworks for large-scale failures, and the recovery method after the large-scale failure is seldom reported. Different from telecommunication networks, the traffic service is inseparable; and the much more services survive in the damaged network, the safer the operation of smart grids. Therefore, the objective of network recovery in smart grids is to maximize the surviving services so as to ensure the safe and stable operation of smart grids. In this paper, to maximize the surviving services after large-scale failures, a multiple-stage network recovery model has been established, and we decompose the multi-stage network recovery problem into multiple single-stage problems. A potential energy-based heuristic algorithm has been proposed to solve the single-stage network recovery problem. The damaged links are rationally arranged at different stages to maximize the number of damaged services in each stage, and to maximize the number of damaged services in the entire recovery process. The simulation results demonstrate that the algorithm has a strong applicability and it is also time-efficient.

The paper is organized as follows: the multi-stage network recovery in smart grids is introduced in Sect. 2; the problem of network recovery is formulated in Sect. 3; In Sect. 4, a heuristic algorithm is proposed; the simulation experiments are carried out and the time complexity is analyzed in Sect. 5; and the conclusion can be obtained in Sect. 6.

2 Multi-stage Network Recovery in Smart Grids

When a large-scale failure occurs in communication networks of smart grids, network recovery needs to be rapidly implemented. However, recovery resources are influenced by the time and geographical location, and network recovery cannot be fully carried out at the same time. During the entire recovery process, network resources need to be returned to the recovery site in batches. Therefore, network recovery can be carried out in multiple stages. In the multi-stage network recovery, the early recovery stages will affect the latter recovery work. The remaining recovery resources in the early stages can also be utilized in the latter recovery process. Also, the pre-repaired links may be used in the latter recovery process. Part of the recovery network recovered in the early stages can still provide services for the latter stages. Therefore, when the total recovery process is planned, recovery resources are first allocated at each stage, and then the damaged network components are determined to be recovered. Finally, the entire recovery process can meet the requirements of smart grids as quickly as possible.

In the multi-stage recovery process of the power communication network, different strategies will lead to different recovery results. Considering the example in Fig. 1, there are 4 damaged links and 7 damaged services. In order to illustrate the problem, assuming that the recovery resources provided in each stage can only repair one damaged link. There are four different recovery sequences to recover the network. Different recovery sequences are shown in Fig. 2. The link (1, 3), link (2, 8), link (2, 7), and link (5, 11) are listed in Fig. 2 (a). The link (2, 7), link (1, 3), link (2, 8) and link (5, 11) are given in Fig. 2 (b). The link (2, 8), link (1, 3), link (2, 7), and link (5, 11) are provided in Fig. 2 (c). The link (5, 11), link (1, 3), link (2, 7), and link (2, 8) are described in Fig. 2 (d).

In Fig. 2 (a) and Fig. 2 (c), i.e. in the first and second stages, more damaged services have been restored; in the third and fourth stages as shown in Fig. 2 (b) and (d), the damaged services increase. In order to recover more damaged services timely, the strategy is preferred. However, after the first stage, the number of restored services are 3 and 2 as shown in Fig. 2 (a) and Fig. 2 (b), respectively. The recovery sequence as shown in Fig. 2 (a) is most appropriate. Therefore, the different strategies will result in different recovery effects for the communication network of smart grids.

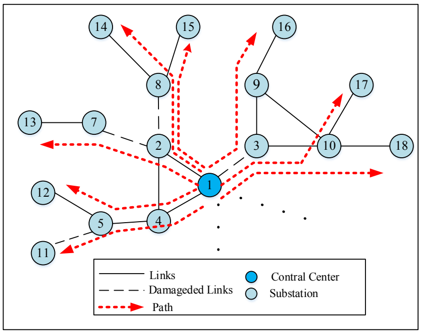

Fig. 1. The example of network recovery in smart grids

It can be seen from Fig. 2, it is an urgent problem to recover as many services as possible timely after large-scale failures of power communication networks. To solve this problem, a multi-stage mathematical model for network recovery is established to

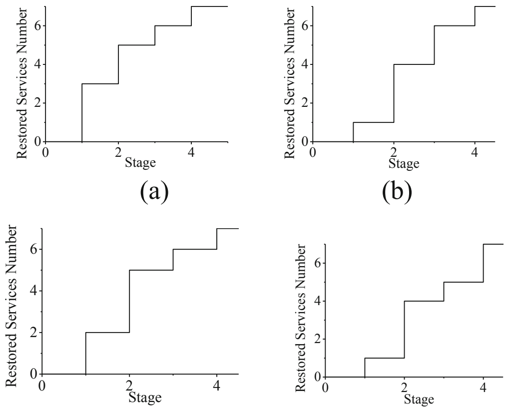

Fig. 2. The results of different recovery sequences

determine which damaged links should be recovered in each stage, so as to maximize the number of surviving services during the entire recovery process.

3 Problem Formulation

A communication network plays an important role in smart grids, and it is responsible for exchanging information between substations and regional control centers. The scale of the communication network is particularly large, sometimes there are more than 100 nodes in the communication network of smart grids. In addition, the traffic of the service cannot be split and the amount of the traffic is integer-valued. The communication services in smart grids are frequently converged to the control center.

In this paper, our assumptions under large-scale failures scenarios are as follows:

1. At least 10% of physical links are damaged;
2. The damaged links will result in the disruption of services;
3. Repairing damaged links takes resources which consist of time and human labors, and the supply of resources is staged.

We model a communication network in smart grids as an undirected graph $G(V, E)$ where V is the set of nodes and E is the set of links. The communication network in smart grids is regarded as an integer multi-commodity supply graph. Θ is the set of services. Each service can be represented by θ represents a service with the source node $s(\theta)$ and the destination node $t(\theta)$. Each link (i, j) belongs to E with the capacity C_{ij}. In order to describe the damaged network, we define E^D as the set of damaged links and E^{DR} as the set of recovered links. Let us define $f(\theta)$ as the flag, which represents if there is a path for the service θ in the graph G. If the path does not exist, $\theta = 0$; otherwise, $\theta = 1$. The objective function is to maximize the number of surviving services in the damaged network.

The flow balance constraint is presented in (2), where x_{ijk}^{θ} represents if the services θ traverses the link (i,j) at the stage k, going from the node i to the node j. If it functions,

$x_{ijk}^{\theta} = 1$; otherwise, $x_{ijk}^{\theta} = 0$. The capacity constraint is presented in (3), where q_{ijl} represents that if the damaged link (i,j) is repaired in stage *l*. When the damaged link (i,j) is recovered at the stage *l*, $q_{ijl} = 1$; otherwise, $q_{ijl} = 0$.

The recovery constraint is presented in (4). In (4), R_l represents the recovery resource of stage *l*. Each damaged link can be repaired once at all recovery stages, as shown in (5). Also, f_k^{θ} is introduced to represent the service θ in (6), where $t(\theta)$ refers to the destination node of the service θ. If there is a path for the service θ after *k* stages, and $j = t(\theta)$, $f_k^{\theta} = 1$; otherwise, $f_k^{\theta} = 0$. In addition, each service θ can only find the path once at all recovery stages, as shown in (7).

The multi-stage network recovery problem can be formulated as follows:

Objective Function:

$$\max \sum_{k=1}^{K} \sum_{\theta \in \Theta} f_k^{\theta} \tag{1}$$

S.t.:

$$\sum_{(i,j) \in E} x_{ijk}^{\theta} - \sum_{(j,i) \in E} x_{jik}^{\theta} = \begin{cases} 1 & i = s(\theta) \\ -1 & i = t(\theta) \\ 0 & others \end{cases} \tag{2}$$

$$\sum_{\theta \in \Theta} x_{ijk}^{\theta} b^{\theta} \le s_{ij} + (C_{ij} - s_{ij}) \sum_{l=1}^{k} q_{ijl} \tag{3}$$

$$\sum_{l=1}^{k} \sum_{(i,j) \in L} q_{ijl} r_{ij} \le \sum_{l=1}^{k} R_l \tag{4}$$

$$\sum_{k=1}^{K} q_{ijk} \le 1 \tag{5}$$

$$f_k^{\theta} = x_{ijk}^{\theta} \qquad j = t(\theta) \tag{6}$$

$$\sum_{k=1}^{K} f_k^{\theta} \le 1 \tag{7}$$

4 The Proposed Algorithm

The problem described above is 0–1 programming, which is NP-hard. The computation time will increase exponentially as the number of damaged links increase, especially when the extent of failures is larger. Therefore, an(a) approximation or heuristic algorithm should be proposed to solve the optimization problem.

In this paper, we proposed an algorithm based on potential energy. First, the multi-stage recovery problem is decomposed into *k* single-stage recovery problems with the same objective which is to maximize the number of surviving services in the damaged network. Second, the single recovery problem can be solved one by one to recover the damaged links at each stage, and a local optimum result can be obtained for the multi-stage recovery problem. Finally, all local optimum results are combined as the approximation optimum result for the multi-stage recovery problem.

Here a heuristic algorithm is proposed to solve the single recovery problem considering the characteristic of smart grids. First, in order to accurately measure the damaged links, the concept of potential energy from electromagnetic theory is adopted. The recovery resources of damaged links are taken into account to reduce or avoid the effect of only considering the distance in the algorithm. Therefore, the potential energy of a damaged link is defined in (8), where len_{ij} represents the distance from the damaged link (i,j) to the regional control center, and r_{ij} refers to the resource of repairing the damaged link (i, j). The potential energy of the damaged link can be described as the priority. The damaged links, which have the greater potential energy, will be repaired first.

$$E_{ij} = \frac{1}{len_{ij} * r_{ij}} \tag{8}$$

Algorithm:

Input: Supply graph G, the services set Θ, the set of restored service Θ_1, the set of damaged links L, the set of repaired links for each stage L_k;

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Decompose the multi-stage recovery problem into K
  single-stage recovery problems
Calculate the potential energy E_ij of all damaged links;
Sort the damaged links in descending order by E_ij;
while k ≤ K do
  while L ≠ ϕ and R_k ≥ 0 do
    Move the damaged link (i,j) with the maximum of
    E_ij from L to L_k;
    R_k = R_k − r_ij
  k=k+1;
Repair the damaged links in L to L_K; and update G
for θ ∈ Θ do
  Find the path of θ by using Dijkstra' algorithm;
  if find the path then
    Move θ from Θ to Θ_1;
    Update G;
Calculate the objective function according to Θ_1;
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In the algorithm, len_{ij} can be obtained by using Dijkstra's algorithm, and the damaged links (i,j) will be sorted in descending order by E_{ij}. At each stage, the damaged links are selected one by one, and the algorithm will terminate when there is no stage or damaged links left. The number of restored services can be obtained by calculating the shortest path of θ using Dijkstra's algorithm.

5 Computational Experiments

In order to verify the performance of the proposed algorithm under the conditions of different numbers of stages and services, two experiments are designed. The optimal result is obtained according to the enumeration algorithm [12, 13]. In addition, the two experiments are implemented by using C++. In the two experiments, first, an undirected network with n nodes is designed. The capacity of each link C_{ij} randomly distributes on [1, 40]; after large-scale failures, the capacity of damaged links decreases to s_{ij}, which randomly distributes on [0,C_{ij}]. The resources of repairing the damaged link (i,j), r_{ij}, distributes on [0,$C_{ij} - S_{ij}$]. Moreover, the number of services in the undirected network is m, and the bandwidth requirement for each service distributes on [1, 4] unit(s) at random. The number of recovery stages is K, and resources of each stage randomly distributes on $mR/n(2*K)$, $2mR/nK$, where R represents the available resources. There are two experiments to be designed to validate the performance of the proposed heuristic algorithm under the different number of recovery stages and services in the network.

5.1 Different Network Experiment Results

In the first experiment, the communication network with 50 nodes is designed and the number of services are {50, 60, 70, 80, 90, 100}, respectively; after the large-scale failure, the number of damaged services are {28, 30, 36, 40, 44, 50}, respectively. The recovery stages, K, are {3, 5, 7}. The recovery results are shown in Fig. 3.

It can be seen from the Fig. 3 that the gap between the optimal and the recovery result of different stages is becoming smaller with the increase of the number services. Especially the higher the recovery stages, the more the number of recovered services, and the better the performance of the proposed algorithm has.

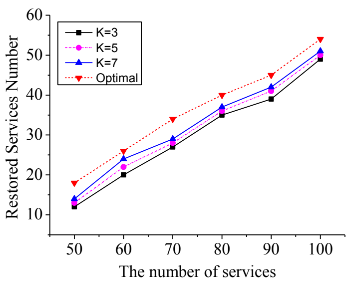

Fig. 3. The recovery results in the network with 50 nodes

In the second experiment, the communication network with 100 nodes is designed and the number of services are {100, 110, 120, 130, 140, 150}, respectively; after large-scale failures, the number of damaged services are {42, 48, 50, 56, 60, 63}, respectively. The number of stages, K, are {3, 5, 7}. The recovery results are shown in Fig. 4.

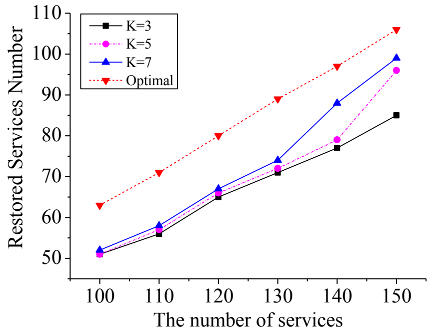

Fig. 4. The recovery results in the network with 100 nodes

It can be seen from Fig. 4 that the gap between the optimal and the proposed algorithm is becoming smaller with the increase of the number of services. At the same time, the performance is very close under the scenios of different number of recovery stages when the number of services is small.

5.2 Time Complexity

In the algorithm proposed here, the time complexity mainly depends on the step 2 and 11. In the step 2, Dijkstra's algorithm is used to calculate the potential energies of all damaged links [14]. The time complexity of the algorithm is $O(nlg(n))$, where n is the number of nodes in the network [15]. In the step 2, assume that the number of damaged links is S, so the time complexity of the step 2 is $S * O(nlg(n))$. In the step 11, the route search is still based on Dijkstra's algorithm, which is similar to the time complexity of step 2. Therefore, the time complexity of the step 11 is $M * O(nlg(n))$, where M is the number of damaged services. In summary, the time complexity of the proposed algorithm is $(2M + S) * O(nlg(n))$.

The optimal solution is obtained according to the enumeration algorithm. In the enumeration algorithm, assume that the communication network with a number of damaged components is S, the number of combinations is at most 2^S, so the time complexity is $O(2^S)$. In a word, the time complexity of the two algorithms is as follows (Table 1).

Table 1. Time complexity of algorithms

Algorithm	The Proposed Algorithm	The Enumeration algorithm
Time complexity	$(2M + S) * O(nlg(n))$	$O(2^S)$

It can be seen from the description above, that the time complexity of the proposed algorithm is linear, while the enumeration algorithm is exponential. For large-scale failures, when both S and n are large, and the enumeration algorithm has high computational complexity. Therefore, in terms of time complexity, the proposed algorithm is better.

6 Conclusion

With the continuous development of smart grids, the structure of smart grids becomes more and more complex, and the incidence of network failures is also increasing. If the damaged network cannot be recovered timely, greater threat will be brought to the secure and stable operation of smart grids. In order to solve the problem, a heuristic algorithm has been proposed. First, the multi-stages recovery problem is decomposed into k single-stage recovery problems. Second, each single-stage recovery problem is solved using a potential energy-based algorithm. Finally, we group all single recovery results and regard them as the approximation optimum result for the multi-stages recovery problem. The simulation results demonstrate that the heuristic algorithm has strong applicability and time-efficient. 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 failures.

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