A Backup Algorithm for Power Grid Based on Regional Fault in the Network Virtualization Environment

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***Abstract*—This paper studies the power network based on the problem of regional fault and unreasonable network design in the network virtualization environment (NV). We propose a network backup algorithm: RSPA (Region-based Fault Tolerant Algorithm based on Sampling Points). The objective of RSPA is promoting the robustness of the entire network to regional faults.**

In the simulation experiment, this paper analyzes the network modeling and topological characteristics of a three-tier power grid in NV. We use the LSRA (Landmark-based Source Routing Algorithm) and PRFAA (Probabilistic Region Failure-Aware Algorithm) as the control group which are widely used in power grid. We investigate the performance of different algorithms and the state of fault generation. The results of the simulation we performed in this paper have shown that RSPA is superior to the rest of the algorithm.

***Index Terms*—Power Grid, Network Virtualization, Regional Fault, Backup Algorithm**

I. Introduction

WITH the development of power grid technology, the users' requirements for the reliability of the power supply have been continuously improved. The smart grid has become an inevitable trend of power grid technology development and an inevitable choice of social and economic development. The smart grid is the source and driving force to promote the development of the power grid. It is also the key technology field of the smart grid construction. Therefore, it is very important to study the reliability of the smart grid.

Although little can be done to predict the random occurrence and scale of such disasters, mitigating their consequences are still possible through the deployment of extra resources in the large-scale disaster region failure. The typical approach followed by network operators to provide service continuity in the event of a large-scale disaster failure is to allocate additional backup optical links as this would create more alternate paths. However, because both primary optical links and backup optical links are vulnerable to the same impact induced by a disaster, increasing network redundancy at the optical physical medium is considered spatially-inefficient and very costly [Meth].

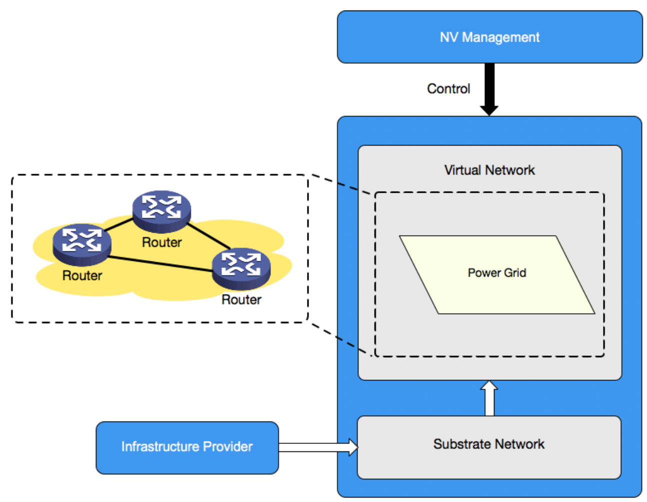


Fig. 1: the architecture of NV

This paper studies the problem of regional failure of the network virtualization environment. The network virtualization deals with the virtualization of network functions usually performed by dedicated hardware devices. Both industry and academia are taking advantage of the network virtualization for boosting innovation and providing flexibility in network management [7].

In NV, the network is divided into the substrate network (SN) and virtual network (VN) [7]. The roles in the network virtualization model include infrastructure provider (InP) and service providers (SP). SP combines the functions that VN provides for the outside world into services shown in Fig.1. SN contains specific network components provided by InP, such as the power communication network and the power grid [8]. NVMA (NV Management) is responsible for resource management and network coordination. The algorithms of this paper run on the NVMA layer, which arranges and optimize the internal power communication network of VN. Unless otherwise specified, any network structures referred to later in this paper are within VN.

In order to solve the problem of regional failure, we introduced the wireless network backup method. Meanwhile, recent development in point-to-point (P2P) wireless technology, such as millimeter-wave and free space optics, has greatly enhanced the capacity, reliability, reachability, and connection stability to the degree that makes it a potential candidate solution for medium diversification. In addition, wireless sensors cost much less than optical fiber links. The wireless communication mode can avoid complicated communication wiring and can also be installed and installed in harsh environments. The main reasons are that it is easier for wireless nodes to collect weak signals. It is very difficult to collect the weak signal by the fault transient distance measurement method, and the wireless network can play a crucial role in it. In the transmission line fault detection and substation automation, wireless networks have been widely used. As an effective complement to other networking methods, wireless networks have also gained a wide range of applications.

The rest of this paper is organized as follows.

- Analyze the complexity of the grid structure and the characteristics of the regional fault.
- Combined with the design requirements of the network, this paper presents a sample-based backup algorithm that combines cost constraints.
- We propose a specific backup algorithm to solve this problem.
- The simulation experiment of the backup algorithm is carried out. By comparing the different algorithms, we illustrate the performance of the algorithm.

The main contributions are as follows. (1) A network-backup scheme based on NV environment is proposed to promoting the robustness of the power grid against the Regional failures. (2) A fault model of smart grid is designed to describe the problem space. (3) The backup algorithm of the sampling points based on the fault model are provided.

II. RELATED WORKS

NV has challenges to be overcome, from small NV deployments to performance issues, but especially NVMA-related issues [8]. The project in [9] provides an architecture for deploying and managing virtual network functions in a cloud environment using open standards. Although some scholars have proposed the idea of adding multiple physically independent topologies to improve network vulnerability [17], there is a lack of comparative research on various backup strategies. Their effectiveness has not yet been achieved in the actual power communication network. The topological structure of the primary power network has been fully studied. Therefore, it is necessary to carry on the thorough analysis to the topology of the power communication network and compare the validity of the existing backup strategy.

The majority of existing work on resilient network design has mainly focused on mitigating isolated single or multiple link failures [Meth]. The subject of large-scale correlated failures has only recently started to draw attention. Research in this field is largely concerned with issues of modeling disaster region failures and measuring their impact [Meth], as well as identifying the vulnerability of network infrastructures to disasters [Meth].

In this paper, we address the challenge of providing the necessary measures to protect optical network infrastructures from random disasters. In particular, we show that the wireless network backup method can potentially overcome the limited performance of wired infrastructure.

III. REGIONAL FAILURE ANALYSIS

The main task of this section is to mathematically define regional faults and then to draw a specific description of the problem. In order to describe the problem vividly, we introduce a simple network as an example for illustration. The simulation experiment uses the backbone network topology of China's three-tier power grid. Fig.2 shows this topology G1. The radius of the fault marked with a gray shaded area is 100km. The center of fault in this area is (600km, 400km). Table I shows the definition of mathematical functions and parameters.

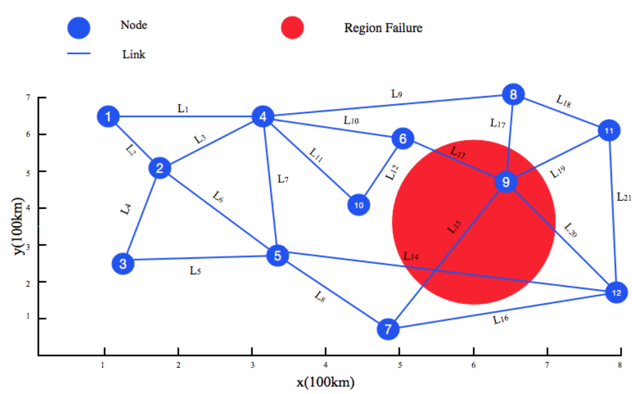


Fig. 2: G1

A. Mathematical Definition

1) Network Diameter: D(G) refers to the maximum distance between any two nodes in G.

2) Binary regional fault function: f (C, r) Indicates the influence range of a regional fault. C indicates the fault center, r indicates the fault radius. The regional fault f1 in Fig.2 can be expressed as follows.

$$f = (C, r) \tag{1}$$

$$f1 = (C_1, 1), C_1 = (6, 4) \tag{2}$$

3) Link identification function: P(L | f) indicates whether link L is affected by fault f.

$$P(L|f) = \begin{cases} 1, \ L\, intersect\, f \\ 0, \ L\, not\, intersect\, f \end{cases} \tag{3}$$

TABLE I: Definition

Definition	Description
G(V, E)	G represents the network topology (V represents the nodes set) (E represents the edge set)
W	the total cost
w	the unit backup cost
D(G)	the maximum distance between any two nodes in G
f(C, r)	the influence range of the regional fault (C represents the fault center) (r represents the fault radius)
P(L | f)	the link(L) is affected by the fault (f) or not
PS(L)	the total number of failures that the link has passed
d(f)	the total number of links in the fault area
PSD(L)	PS(L) combined with fault density
PSD(E)	the sum of the PSD(L) of the links in E
N(G,f)	the evaluation of network performance based on f
Ew	the total number of the workable links in E

We can draw the corresponding results of L13, L14, L15, L16 and f1 from Fig.2 (L13, L14, L15 are within the f1 range, L16 is not within the f1 range).

$$P(L13|f1) = P(L14|f1) = P(L15|f1) = 1 \tag{4}$$

$$P(L16|f1) = 0 \tag{5}$$

4) Link failure statistics function: PS (L) indicates how many failures this link may be affected by.

$$PS(L) = \sum_{i=1}^{n} P(L|f_i) \tag{6}$$

5) Fault density function: d(f) indicates how many links the fault has passed. This shows the impact of this failure on the entire network. In general, if there is a node in this fault, the area is more dense. Equation 8 describes d(f1) in G1.

$$d(f) = \sum_{k=1}^{n} P(L_k|f)/(f.r)^2 \tag{7}$$

$$d(f1) = 6/1^2 = 6 \tag{8}$$

6) Network evaluation function: N(G, f) indicates the evaluation of network performance based on regional failures. Equation 9 describes N(G, f).

$$N(G, f) = (E_w/E) \mid f \tag{9}$$

$$E_w = workable \quad links \quad in \quad E \tag{10}$$

B. Regional Fault

In order to simulate the model, we need to make some constraints on the specific problems and mathematical definitions to get the solution.

First, we use the f (C, r) to describe the regional fault. The difficulty of the study is that f is completely random(C and r are randomly chosen in the positive real number domain). In order to reduce the difficulty of solving this problem, we make some weakening constraints on f according to some empirical conditions. For the network topology G (V, E), the regional fault f (C, r):

- For the fault f (C, r), if the distance from C to any node is greater than r, then the fault has no effect on the network.
  So we want to get rid of this situation. The mathematical constraint we draw is MIN (C, V) $>$ r.
- For the fault f (C, r), if r is large, this fault is very destructive and can not be solved by backup.
  Suppose that r $>=$ D(G1)/2 in G1. When c happens randomly, at least one f (C, r) will cover the entire G1. Fig.3 shows that G1 is affected by f(C, r) when r = D (G1)/2. In this case, it is pointless to analyze the network structure because all the links are destroyed by this fault.
  The mathematical constraint we draw is r $<$ 1/2D(G). In general, we simply represent r = D(G)/k, k$>$2.

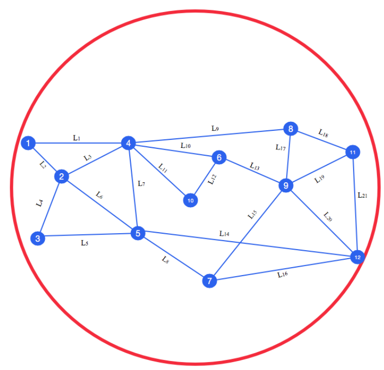


Fig. 3: r = D(G1)/2

- Cost constraints. The wireless link has limited communication range. When we back up, we either choose to back up the entire link or choose not to back up. The partial backup of a link is meaningless. In order to simplify the problem, we default the cost of wireless backup only with the link length and wireless transmission.

From the above constraints, we can draw some important conclusions:

- In the simulation experiment, we take the fault radius as the input of the algorithm. In the actual environment, the scope of the failure is an important indicator to evaluate the damage of the fault. So we choose fault radius as the core parameter. Different feedback from the network represents resistance to different levels of regional failure.
- The higher the domain density of the fault area through the link, the lower the resistance. Assume that only two fault zones f1 and f2 are considered, as shown in Fig.4.

$$PS(L2) = P(L2|f1) + P(L2|f2) = 1 \tag{11}$$

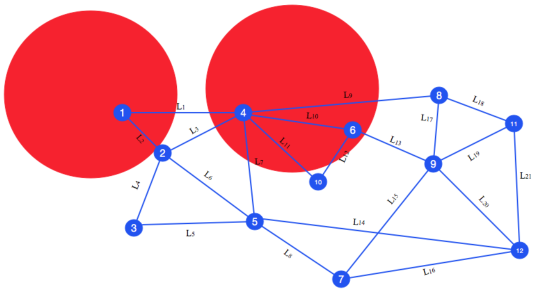


Fig. 4: two fault zones

$$PS(L12) = P(L12|f1) + P(L12|f2) = 1 \quad (12)$$

Because of PS (L2) = PS (L12), we should randomly select a link for backup. But d(f1) = 2 $<$ d(f2) = 7, this shows that f2 causes more link failures. So L12 should take precedence over L2. In other words, L12 is more likely to be in the center of the network.

So we introduce the PSD(L) and PSD(E) (E represents the link set). The smaller the PSD function value, the greater its network resistance.

$$PSD(L) = \sum_{i=1}^{n} P(L|f_i) \cdot d(f_i) \quad (13)$$

$$PSD(E) = \sum_{E} PSD(L) \quad (14)$$

C. *Problem model*

For network G, we need to find the result set R to satisfy the following three formulas (E represents the link set of G, W represents the total cost, w represents the unit cost).

$$R \subseteq E \quad (15)$$

$$wR <= W \quad (16)$$

$$min(PSD(E - R)) \quad (17)$$

The above constraint indicates that we require a set of edges that satisfy the cost constraint. This set will minimize the set of PSD functions for the remaining edges. We explain the algorithm in the next chapter.

IV. Algorithm

In order to solve the problem in the previous section, we propose a region-based fault tolerant algorithm based on sampling points (RSPA).

Before describing the RSPA, we must first determine the simulation method of regional failure. The more sampling points we choose, the more accurate the data we draw. However, due to the constraints of the actual environment and simulation conditions, this article selects the sampling points according to the specific conditions of the topology.

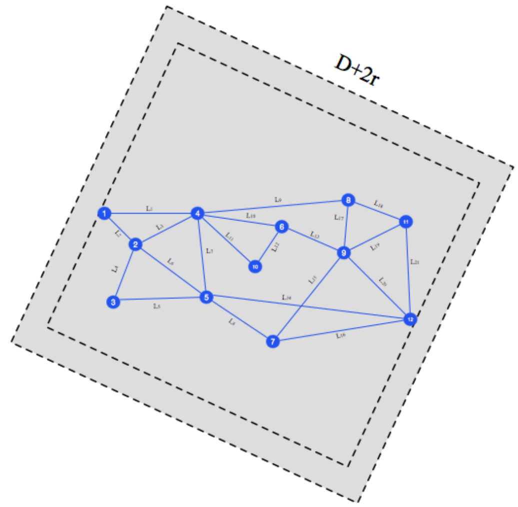


Fig. 5: sampling ranges

A. *Simulation method*

1) Sampling range: It is the range affected by the fault. In Fig. 5, D is the diameter of the network and r is the radius of the fault. The area of the dotted line enclosed by a square of length D + 2r in the figure can be regarded as the domain of the fault center point. We can prove that the failure of the area may affect the topology only when the fault center is in the domain. Otherwise, the shortest distance from the node to the topology is longer than the fault radius.

B. *Specific algorithm*

First, we show the meaning of the input parameters of the algorithm. G represents the network topology, V represents the network node set, E represents the network edge set, W represents the total cost, w represents the unit backup cost, r represents the fault radius. The result given by the algorithm is denoted R. See the appendix for the specific algorithm. RSPA is divided into two phases. For the convenience of explanation, we combine the algorithm steps to explain concretely.

1) Sample point generation phase: This section takes G0 as an example to illustrate the concrete realization of the algorithm. Fig.6 shows the topology of G0. We assume that the fault radius is 1km. Fig.7 shows the calculation of network diameter. Fig.8 shows the sampling point generation process.

2) Link inspection phase: Fig.9 shows how to calculate the relationship between link and fault and how to generate the result.

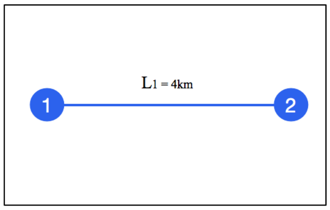


Fig. 6: G0

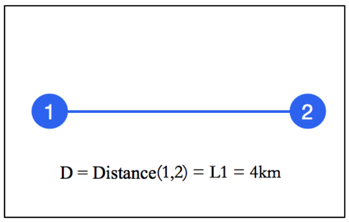


Fig. 7: Calculate network diameter

V. Simulation Experiment

At present, the simulation platform of power network and communication network is still not available. This paper uses the NetworkX simulation package to generate an emulation coupled network and performs simulation experiments on this platform. NetworkX is a Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks. The purpose of the experiment is to validate the model and verify the algorithm. As shown in Fig.10, we use G1 as the simulation network.

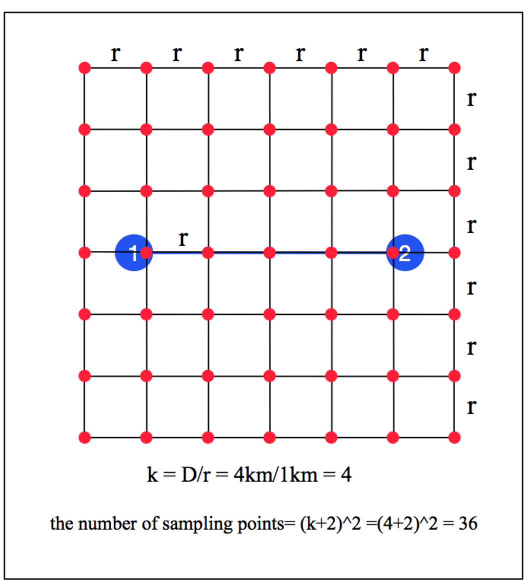


Fig. 8: Generate sampling points

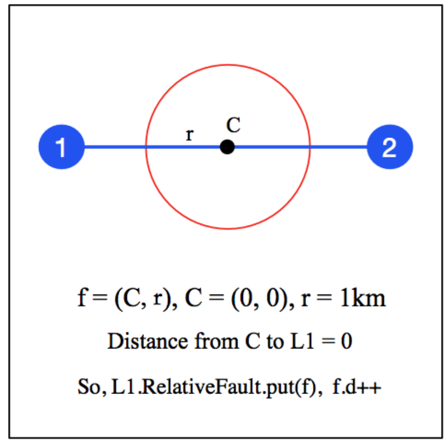


Fig. 9: Link inspection

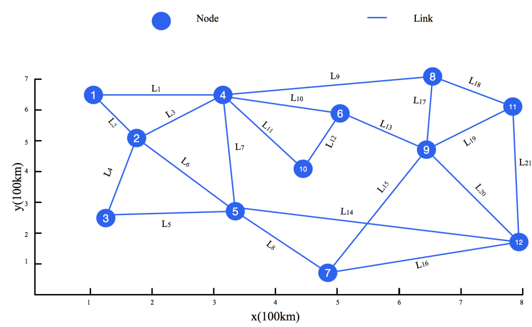


Fig. 10: Simulation Network G1

A. Comparison algorithm

Next, we introduce the comparison algorithm. At present, some algorithms have been proposed for the study of regional faults, and this part has already been partly explained in the previous section. We chose two algorithms in this section as the control group for the experimental effect. LSRA (Landmark-based Source Routing Algorithm) [FAST] uses the geographically distributed intermediate nodes, named landmarks, to reestablish the connection through a shortest path. PRFAA (Probabilistic Region Failure-Aware Algorithm) proposes an Integer Linear Program-based theoretical framework to identify the optimal data center network placement to lead to the minimum data center network failure risk under a region failure.

B. RSPA

According to the algorithm, we can draw the following data. As shown in Fig.11, we can get the diameter of the network through the algorithm. After that we explained the specific calculation process.

$$D = Distance\,(node1, node12) \tag{18}$$

$$D = \sqrt{(node1.x - node12.x)^2 + (node1.y - node12.y)^2} \tag{19}$$

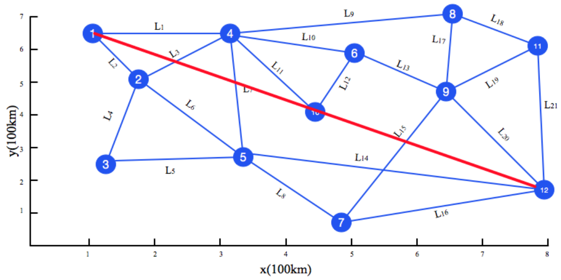


Fig. 11: Diameter

$$D = \sqrt{(1-8)^2 + (6.5-2)^2} = 8.32 \tag{20}$$

As shown in Fig.12, We show the sampling points when r = D/6 =1.39.

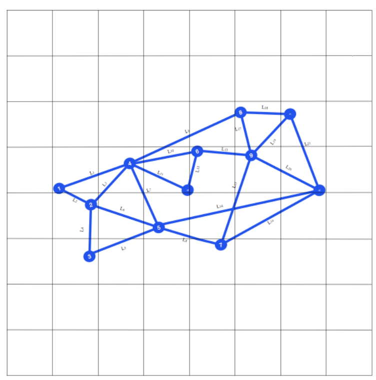


Fig. 12: r = D/6

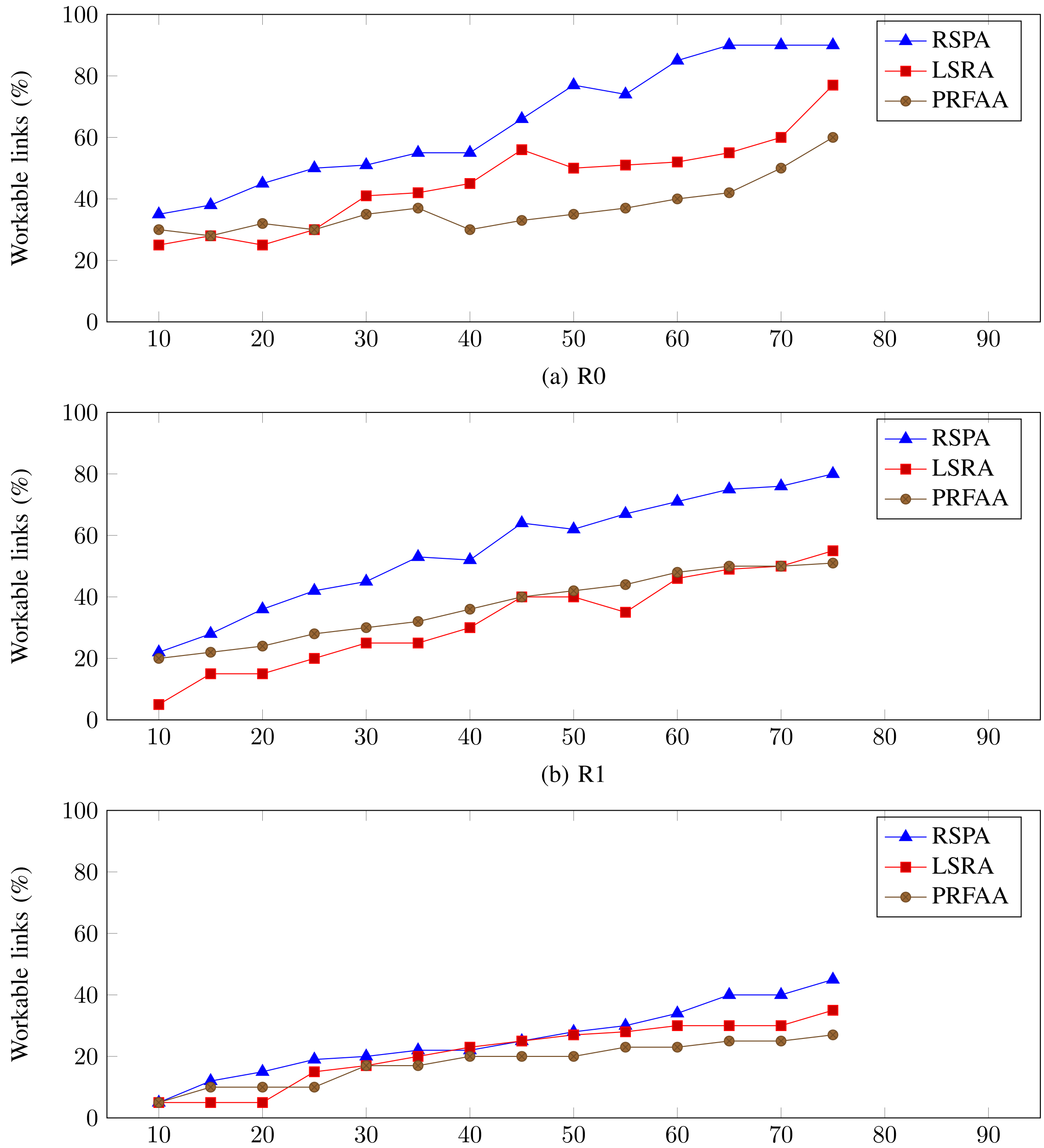
C. Algorithm evaluation

Due to the particularity of regional faults, we take the total cost and the radius of regional faults as input parameters. Fig.13 shows the difference in performance between algorithms when input parameters change. R0, R1 and R2 in the Fig.13 show different fault radiuses (R0 = D/6 = 1.39, R1 = D/4 = 2.08 and R2 = D/2 = 4.16). The abscissa of the Fig.13 indicates the proportion of the backup link(10%-75%). This parameter is proportional to W/w.

VI. Conclusion

We can draw the following conclusions based on the simulation results in the previous section.

- The backup algorithm proposed in this paper effectively improves the robustness of the network against regional failures.
- As the radius of regional failure increases, the damage to the network is greater.



(a) R0

(b) R1

(c) R2

Fig. 13: Simulation results

Acknowledgment

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[1] Ye Y, et al. A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges [J], IEEE Communications Surveys Tutorials, 2013, 15(1):5-20.

Appendix

Algorithm 1 RSPA

```
Input: G, V, E, W, w, r
Output: R
global ArrayFault ← 0
global R ← 0
global k ← 0
function MAIN(G)
    D ← GENERATEDIAMETER(V)
    GENERATEFAULTSET(D,V, r)
    CHECKINFAULT(E)
    E.orderBy(L.psd)
    for L : E do
        if W > wL then
            R.put(L)
            W ← W − wL
        end if
    end for
    return R
end function
function GENERATEDIAMETER(V, r)
    D.length ← 0
    for head : V do
        for tail : V do
            length ← DISTANCE(head, tail)
            if length > D.length then
                D.length ← length
                D.head ← head
                D.tail ← tail
            end if
        end for
    end for
    k ← D/r
    return D
end function
function GENERATEFAULTSET(D, V, r)
    origin ← (head + tail − D − 2r)/2
    for i : range(k + 2) do
        for j : range(k + 2) do
            fault ← (C(origin.x + i ∗ r, origin.x + j ∗ r)r)
            ArrayFault.append(fault)
        end for
    end for
end function
```

Algorithm 2 RSPA-CheckInFault

```
function CHECKINFAULT(E)
    origin ← (head + tail − D − 2r)/2
    for L : E do
        for f : ArrayFault do
            O ← f.c
            H ← L.head
            L ← L.tail
            OH ← DISTANCE(O, H)
            HL ← DISTANCE(H, L)
            OL ← DISTANCE(O, L)
            S ← DISTANCE(S, HL)
            if CHECK( )then
                L.RelativeFault.put(f)
                f.d + +
            end if
        end for
        for L : E do
            L.psd ← L.RelativeFault.sum
        end for
    end for
    function CHECK
        if sign(OH − r)&sign(OT − r) then
            Angle ← sign(OH^2 + HT^2 − OT^2)(OT^2 + HT^2 − OH^2)
            return Angle&(sign(r-S))
        else
            return True
        end if
    end function
end function
```