Journal of Electronics and Information Science (2021) 6: 47-55
Clausius Scientific Press, Canada
DOI: 10.23977/jeis.2021.61008
ISSN 2371-9524

A New Link Isolation Algorithm based on Complex Network Theory for Preventing Cascading Failures in Power Grid

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Keywords: Power Grid, Complex Network, Links Isolation, Vulnerability

Abstract: Weak links is one of the main causes of large-scale blackouts in power systems. How to accurately identify the weakest links so as to disconnect the links that could cause cascading failures when an accident happens to a power system, is a vital research topic for keeping power system safety by preventing large-scale blackouts caused by cascading failures. In this paper, based on complex network theory we first propose a method to identify the weakest links according to vertices second order centrality and links joint vulnerability metric by combining link betweenness and link load level, which is called joint vulnerability method (JVM). Based on JVM, we design a links isolation algorithm when a weakest link failure happens to a power system, which is called joint isolation algorithm (JIA). The simulation results show that JVM could identify the weakest links accurately, and the JIA could avoid large-scale blackouts effectively which plays a guiding role in the optimization of power system safety.

1. Introduction

Power grid [1] is the most essential public infrastructure in modern society, which powers the Internet, transportation networks and others. It is no exaggeration to say that the power grid is rightly celebrated as the single most important engineering feat of the 20th century. In recent years, many researches [2], [3], [4] of large-scale power blackouts show that before the large-scale power blackouts happened, only a few components were faulted at first, while more and more links failure happened because of the weak links. A large-scale power blackouts would happen very quickly if a appropriate links isolation algorithm was not applied to prevent these cascading failures. Therefore, how to identify the weakest links in the grid, and then design a proper links isolation algorithm when an accident happen to the grid are the most two important topics in the study of power grid safety.

At present, there are few achievements related to effective links isolation algorithm. The most popular isolation methods are manual isolation and fault zone isolation. Other automatic isolation schemes have no effective technique. Because the islanding method can isolate the whole grid into separate parts that operate independently, the traditional approach is to adopt islanding method when a fault occurs on a power system. It is generally known that there are two kind of islanding methods: passive islanding [5] and controlled islanding [6]. Passive methods are based on the monitoring of system parameters (such as voltage, current, impedance or power) to perform islanding detection [7], [8]. The drawback of passive islanding is obvious. In the case of passive islanding, the internal power of some power islands will be unbalanced and generator tripping or load shedding has to be applied to the islands, which has a great impact on the user's electricity consumption. Therefore, controlled islanding method has gradually become the research focus. However, most of the controlled islanding methods are related to the power angle characteristics of generator unit, while the computational complexity is very high. It is usually difficult to satisfy the requirements of timeliness, so that the majority of scholars gradually begin to explore new solutions.

Complex network theory provides us with a series of methods to model and study power grids. The functionality of a complex network relies heavily on its structural robustness [9], i.e., whether the network can keep sufficient connectivity when a subset of its vertices or edges is removed. If vertices or edges acting as important functions in the network are removed, the network may face a fatal collapse. In a grid network, the important links also called weak links. Based on vulnerability analysis of complex network theory, this paper first proposes a method JVM to identify the weakest links. Based on JVM method, we design a links isolation algorithm JIA when a weakest link failure happens to a power system. The calculation process is very simple. Simulation results show the effectiveness of the proposed algorithm. The calculation processes of JVM and JIA are very simple, and the details are presented in section Ⅳ. Simulation results show the effectiveness of the proposed algorithm in section Ⅴ.

2. Grid Vulnerability Metrics

Before introducing these metrics, we should know that a grid with N vertices and M transmission lines can be modeled as a complex network $G=\{V, E\}$, where $V=\{1, 2, \dots , N\}$ is the set of vertices and $E \subseteq V \times V$ is the set of edges with $|V| = N$ and $|E| = M$. The adjacency matrix A, where the element A_{ij} equals 1, if vertices v_i and v_j are connected, 0 if they are not. The neighbors of vertex v_i is defined as $V_i=\{j \in V:(i,j) \in E\}$, the degree of vertex v_i is denoted by $k_i=|V_i|$, and the average network degree is denoted by $\langle k \rangle$.

Vertex Second Order Centrality: Kermarrec [10] proposed a distributed second order centrality(SOC) based on a random walk to a network, where each vertex only needs to know its immediate neighborhood without any global information. The vertex currently in charge of the random walk randomly selects one of its neighbors uniformly, and forwards the random walk to the selected vertex with a probability depending on the degree of the two vertices. A distributed algorithm is used to compute the standard deviation of the return times for each vertex based on the Metropolis-Hastings process in which Markov chain is homogeneous and irreducible. A classical discrete time Markov chain is used on the finite state space S to represent the random walk. State v_i means the random walk is at vertex v_i. The standard deviation of vertex v_i is shown as below.

$$\sigma(v_i) = \sqrt{2 \sum_{u \in S} M(v_i, v_j) - |S|(|S| + 1)} \tag{1}$$

Where $M(v_i, v_j)$ represents the expected time starting from v_i state to reach state v_j for the first time. And the SOC of vertex v_i is:

$$C_{SO}(v_i) = \begin{cases} 1/\sigma(v_i), & if\ \sigma(v_i) \neq 0 \\ 0 \ , & if\ \sigma(v_i) = 0 \end{cases} \tag{2}$$

Link Betweenness Centrality: Betweenness centrality (BC) is one of the most popular metrics of complex network theory. Vertex BC first focus on the number of times a vertex acts as a bridge along the shortest paths of vertex couples. The SOC of vertex v is:

$$C_B(v_i) = \sum_{s,t\in V} \frac{g_{st}(v_i)}{g_{st}} \tag{3}$$

Where n_{st} is the total number of the shortest paths from vertex v_s to v_t, and $g_{st}(v_i)$ is the number of those paths that pass through v_i. And the BC of a link e is the sum of the fraction of all-pairs shortest paths that pass through e. So BC of link e is:

$$C_B(e) = \sum_{s,t\in V} \frac{\sigma_{st}(e)}{\sigma_{st}} \tag{4}$$

3. Links Joint Vulnerability Method of Grid

Joint Vulnerability Metric: Based on link BC, this paper proposes a joint vulnerability metric which consider both structural vulnerability and state vulnerability of power grids. The structural vulnerability uses the link BC, and the state vulnerability uses the link load level [11]. The joint vulnerability metric is defined as follows:

$$F(e_{ij}) = 0.5[C_B(e_{ij}) + L(e_{ij})] \tag{5}$$

Where the link BC $Cb(e_{ij})$ is for structural fragility, and the load level $L(e_{ij})$ is for state fragility. And the load level of the link is defined as the ratio of the link active power flows to the maximum link active power flows:

$$L(e_{ij}) = \frac{P(e_{ij})}{P_{max}} \tag{6}$$

Where the larger L is, the larger the load is. The load may be outage (L =0), light load, normal, heavy load and full load (L =1). L is calculated based on actual operating parameters when the system is running. In this paper, the algorithm ignores the change in load level caused by the outage of other links because of the limited response time when performing fault links isolation.

The SOC of each vertex is only used as an auxiliary method to confirm and judge the link is weak or not. The details of the JVM to identify the weakest links is shown below.

Joint Vulnerability Method: To identify the weakest links set of a grid, this method considers both links vulnerability as show in Eq.(6) and vertex SOC. The weakest links set of a grid based on JVM is shown as below:

1. Model a grid network based on topology of the grid;
2. According to Eq.(2) and (7), get the joint vulnerability metric of each link and the SOC of each vertex, and sort links and vertices of the grid by their joint vulnerability value and SOC value from large to small respectively;
3. Attack links one by one according to the link order until the connectivity of the network (the ratio of the number of links that can still run to the total number of links) [12] falls to a threshold T_1, and the attacked link is classified into the temporary link set L_t, and restore the power grid.
4. Remove vertices one by one according to vertices order until the connectivity of the network (the relative size of the largest connected component) [9] drops to a threshold T_2 (T_2>T_1), and classify the attacked node into the temporary vertices set V_t.
5. Eliminate the link in the L_t which either the starting vertex or ending vertex is not in the set V_t, then get the weakest link set L_w.

Since the state and structure are considered in this method, so JVM is closely related to the operating state at each moment of the gird. Therefore, we must update the JVM indicators of links while the power system is operating in order to update the weakest links set.

4. Joint Isolation Algorithm of Grid

In last section, we can get the weakest link set L_w of a grid by JVM. If a failure happens to a link inside the weakest links set L_w, an appropriate links isolation method has to be applied to prevent cascading failures. This paper proposes a new method to isolate weak links when failures happen. The isolation process of new method JIA is as follows:

1. Check whether the failed link is belong to the weakest links set L_w or not;

If it is not, which means the this failure won't cause any cascading failure, there is no need to isolate any link. Otherwise, we have to take the next step in order to prevent cascading failures.

2. Detects the connectivity of links inside the weakest links set L_w;

This step is designed to minimize the links zone of isolation. If the links in the weakest link set L_w is connected well, the links zone to be isolated will be larger. So the proposed solution is: if the links in the weakest link set L_w are completely connected, all the links in the set should be isolated. If they are not completely connected, we have to simulate the isolating of links connected with the failed weak link to check whether cascading failures can occur or not. If it does not lead to s cascading failures to the gird, the link should be isolated and added into the perimeter link set C_2. Otherwise, the link should not be isolated and the vertices of the link should be added into the set C_1.

3. Generate a preliminary fault zone vertices set C_1 and perimeter links set C_2;

Based on exhaustive search [13], this step is trying to obtain the vertices set C_1 and perimeter link set C_2 for the initial fault area. Let the number of vertices in C_1 be l. Attack the weakest links one by one according to their joint vulnerability metric value order until the ratio of the number of links in operation to the number of links that have not been attacked is less than the given threshold, then record the joint vulnerability metric value F_0 of the link attacked now. Then traverse the nodes in C_1 and judge whether the vulnerability index of each link connected with the current node is less than F in turn. If so, put the link into C_2; otherwise, put the node into C_3. Let the number of vertices in C_3 be m. For any child node in the set, search for its subordinate child nodes. If the joint vulnerability metric value of the link connected with the two nodes is less than F_0, put the link into C_2; otherwise, put the subordinate child node into C_4, and then update C_3 with C_4 and then empty C_4. When C_3 is an empty set, the traversal operation of the parent node ends.

4. Generate nodes set C_5 that outside the fault area;

Based on exhaustive search, consider the perimeter node as the root node, and then take the adjacency matrix generated by the link connect with the root node as the judgment condition, at last generate the nodes set C_5 outside the failure area. For the node outside the failure zone but in the perimeter links set C_2, check the frequency of its occurrence in the perimeter set: if the frequency is equal to the node degree, it can be known that the node is an outlier, which should be put into C_1, and the links connected with this node should be deleted from the perimeter links set C_2. If a part of the nodes belong to the generator node set or none belong to the generator node set, they should be put into the failure zone node set and the links connected with this node should be deleted from the perimeter links set C_2.

5. Check the power difference of each isolation zone and make appropriate fine tuning.

Calculate the power difference within each isolation zone. If the difference can reach the basic balance within each isolation area, the isolation algorithm will end, otherwise appropriate changes must be made.

5. Simulation Analysis

This paper adopts the IEEE118 power system [14] as a simulation model, and its topology is shown in Fig.1. The network consists of 118 nodes, 186 lines, 19 generator sets, total power generation of 4377.4 MW, and total load of 4242 MW.

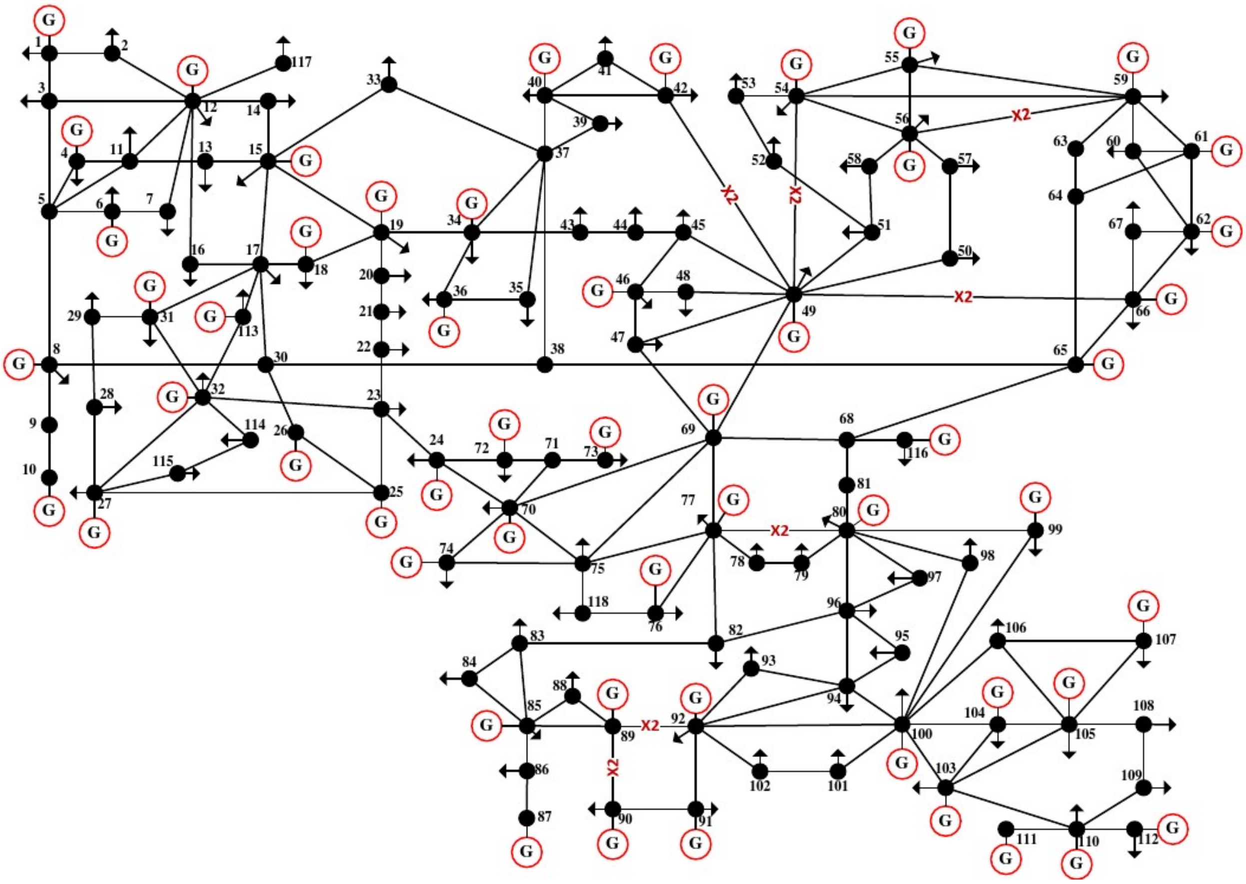

Figure 1: The topological structure of IEEE118 power grid.

The Weakest Links Set based on JVM: In this section, we attack the links according to the order of their joint vulnerability metric value. And we use the remaining connectivity of IEEE118 to evaluate the availability of JVM. Table no 1 presents the remaining connectivity of the grid under the attack of first nine links based on three vulnerability metrics (link betweeness, link load level and link JVM), and Table 2 presents the remaining connectivity of the grid under the attack of next eight links.

Table 1: The remaining connectivity of IEEE118 under the attack of first nine links based on three metrics.

Attack links	Attack links ratio	Link betweenness	Link load level	JVM	Random attack
1	0.54%	97.8	98.4	97.9	98.4
2	1.08%	84.4	97.9	96.8	97.9
3	1.61%	80.7	97.3	94.6	97.3
4	2.15%	79.6	97.3	89.8	96.8
5	2.69%	79.0	96.8	81.7	96.2
6	3.23%	75.3	95.2	59.7	95.7
7	3.76%	74.2	27.4	41.9	95.2
8	4.30%	67.2	18.3	41.4	94.6
9	4.84%	61.8	18.3	38.2	94.1

As shown in Table no 1, the remaining connectivity is reduced to about 62% under links attack based on links betweenness when the number of attack links increases to 4.84% of the total number of links, while the random link attack just reduced to about 91%. It is obviously to say that the link betweenness can be effectively used to evaluate the vulnerability of links. However, it is doubtful that the link with larger betweenness has a greater impact to the power grid when attacking the links, because BC of links cannot help us to distinguish the critical link that causes cascading failures. When the links attacking order consider the load level, the remaining connectivity of the network is quickly reduced only when the first six links have been attacked, but the failures of the first six links have not led to a large reduction in the network connectivity. While for JVM, the remaining connectivity of the network is always reduced quickly.

Therefore, JVM can effectively distinguish the weakest links set. Then, in the nex link isolation process, we use JVM to get the weakest links set. For the process of JVM, let T_1=0.3 and T_2=0.4, then we can get the weakest links set {$e_{38\text{-}65}$, $e_{30\text{-}38}$, $e_{8\text{-}5}$, $e_{65\text{-}68}$, $e_{8\text{-}9}$, $e_{9\text{-}10}$}.

The simulation of links isolation based on JIA: In this simulation, we let the links $e_{8\text{-}9}$ and $e_{30\text{-}38}$ fault respectively to simulate the links isolation based on JIA.

(1) If a failure happens to $e_{8\text{-}9}$.

From Figure.1, we can observe that $e_{38\text{-}65}$, $e_{65\text{-}68}$ are connected with $e_{30\text{-}38}$, and $e_{8\text{-}5}$, $e_{8\text{-}9}$ are connected with $e_{9\text{-}10}$ meanwhile the two groups links are connected via link $e_{8\text{-}30}$. If we isolate the link $e_{8\text{-}30}$ and simulate the power system, we can observe that there is no cascading failure happen. Therefore, the link $e_{8\text{-}30}$ should be isolated. After carrying out a series of processing on the gird with the algorithm of JIA, the isolation result is shown in Figure.2.

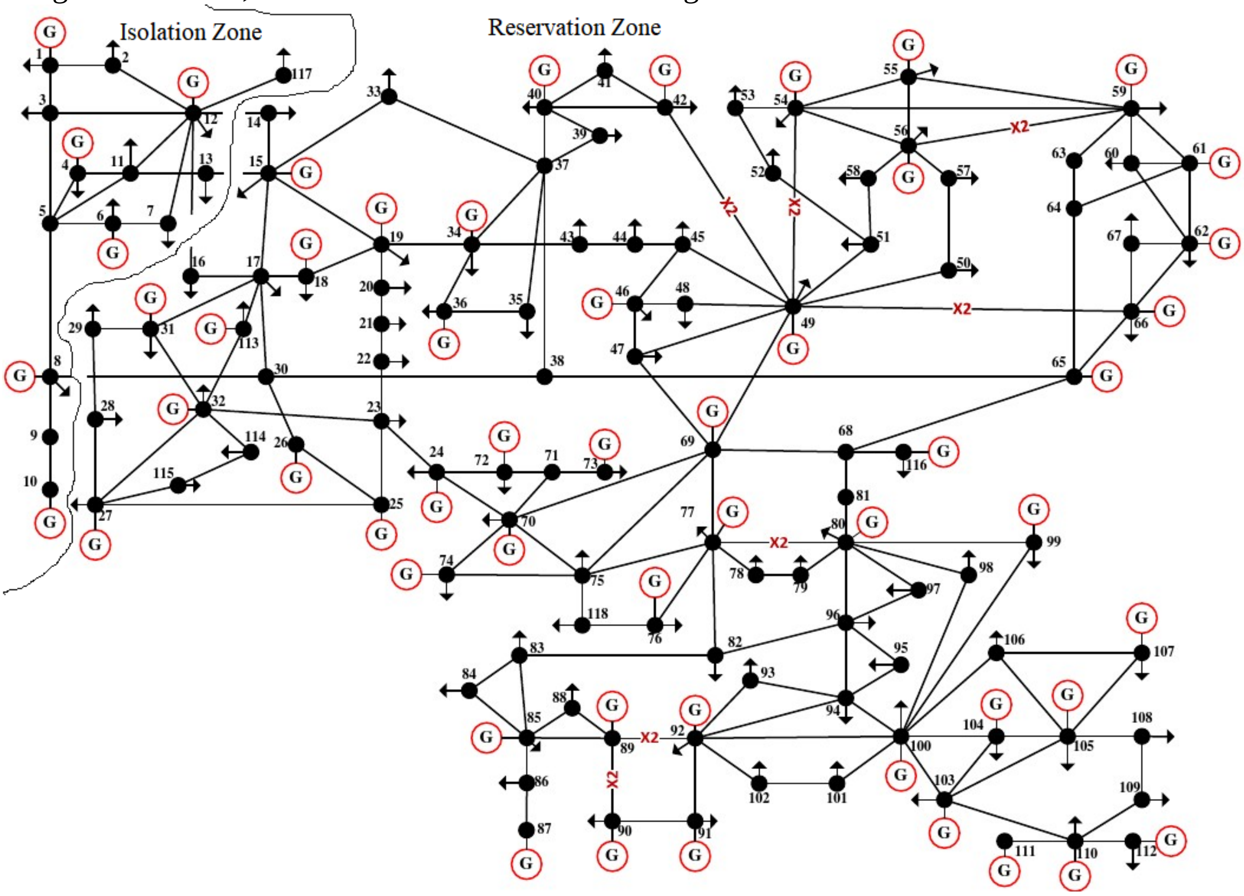

Figure 2: The isolation zone when the link $e_{8\text{-}9}$ failed in the IEEE 118 power grid.

As shown in Figure 2, the isolation links set: {$e_{8\text{-}30}$, $e_{12\text{-}14}$; $e_{12\text{-}16}$; $e_{13\text{-}15}$}, and the power difference of each area is shown in Table no 2. The isolation zone is isolated in the upper left corner. Without considering the network loss, Table no 2 shows that the power generation in the reservation zone is 3842.4 MW, the load is 3823 MW, and the degree of imbalance is only 0.44%. The reservation zone is basically in equilibrium and can operate independently without other optimization measures. Moreover, there are only four links in the isolation zone, and the network recovery after the isolation is quite simple.

Table 2: The power difference after links isolation when the link $e_{8\text{-}9}$ failed.

Total power generation (MW)	Total load(MW)	Difference(MW)	Imbalance rate	Total power generation (MW)
Isolation zone	535	419	116	2.65
Reservation zone	3842.4	3823	19.4	0.44
Total	4377.4	4242	-	-

(2) If a failure happens to $e_{30\text{-}38}$.

From Figure.1, we can observe that $e_{38\text{-}65}$, $e_{65\text{-}68}$ and $e_{30\text{-}38}$ are connected with $e_{8\text{-}30}$, and $e_{8\text{-}5}$, $e_{8\text{-}9}$ and $e_{9\text{-}10}$ are alos connected with $e_{8\text{-}30}$. meanwhile the two groups links are connected via link $e_{8\text{-}30}$. If we isolate the link $e_{8\text{-}30}$, and simulate the power system, we can observe that there is no cascading failure happen. Therefore, the link $e_{8\text{-}30}$, should be isolated. After carrying out a series of processing on the gird with the algorithm of JIA, the isolation result is shown in Figure.3.

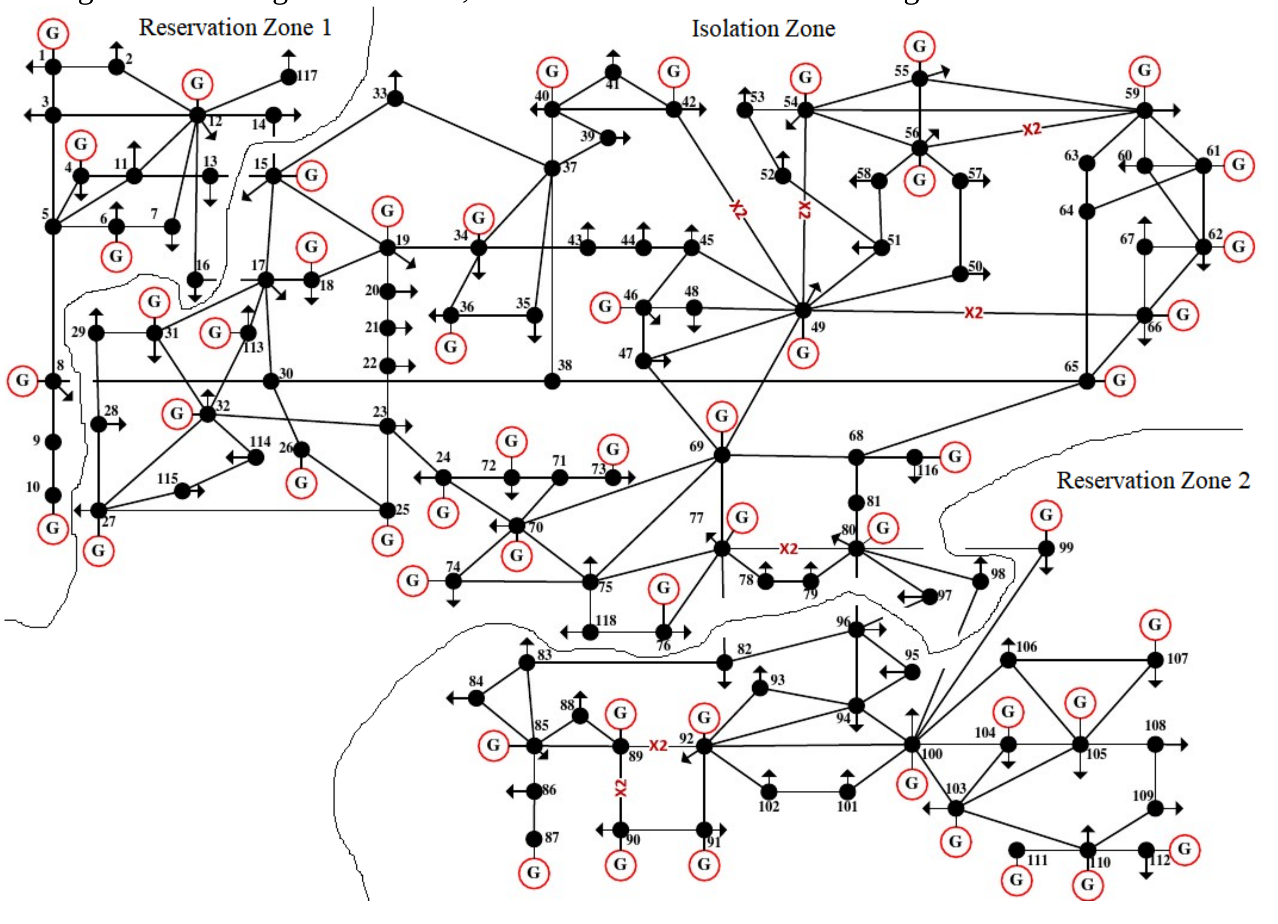

Figure 3: The isolation zone when the link $e_{30\text{-}38}$, failed in the IEEE 118 power grid.

As shown in Figure 3, the isolation links set: {$e_{30\text{-}8}$, $e_{17\text{-}16}$, $e_{15\text{-}13}$, $e_{15\text{-}14}$, $e_{77\text{-}82}$, $e_{80\text{-}96}$, $e_{80\text{-}99}$, $e_{97\text{-}96}$, $e_{98\text{-}100}$}, and the power difference of each area is shown in Table no 3. The isolation zone is isolated in the middle zone. Without considering the network loss, Table no 3 shows that the power generation in the reservation zone is 3842.4 MW, the load is 3823 MW, and the imbalance degree of reservation zone 1 and isolation zone are 1.76% and 1.49% respectively. The reservation zone 1 is basically in equilibrium and can operate independently without other optimization measures. However, the amount of electricity generated in the reservation zone 2 is slightly lower than the load. So a small number of low load components need to be isolated in order to maintain all parts in normal operation. Moreover, there are only nine links in the isolation zone for the grid with 186 links, so the network recovery after the isolation is simple.

Table 3: The power difference after links isolation when the link $e_{30\text{-}38}$ failed.

Area	Total power generation (MW)	Total load(MW)	Difference(MW)	Imbalance rate
Reservation zone 1	535	458	77	1.76
Reservation zone 2	939	946	-7	-0.16
Isolation zone	2903.4	2838	65.4	1.49
Total	4377.4	4242	-	-

The analysis of the above two examples implies that the method JVM can evaluates the links vulnerability effectively and the algorithm JIA can avoid large-scale blackouts effectively which plays a guiding role in the optimization of power system safety.

6. Conclusion

To efficiently evaluate the links vulnerability of grids. This paper first propose a joint vulnerability metric which consider both structural vulnerability and state vulnerability of power grids. The structural vulnerability uses the link BC, and the state vulnerability uses the link load level. Based on the joint vulnerability metric, reference node SOC metric, this paper propose JVM to evaluate the links vulnerability. At last, to effectively prevent large-scale blackouts caused by cascading failures when a failure happen to a weak link, based on the weakest links set generated by JVM, this paper propose a new algorithm JIA to apply links isolation when a failure happen to a weak link. And the simulation results show that the method JVM can evaluates the links vulnerability effectively and the algorithm JIA can avoid large-scale blackouts effectively which plays a guiding role in the optimization of power system safety.

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