Comprehensive risk assessment method of catastrophic accident based on complex network properties

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Abstract. On the macro level, the structural properties of the network and the electrical characteristics of the micro components determine the risk of cascading failures. And the cascading failures, as a process with dynamic development, not only the direct risk but also potential risk should be considered. In this paper, comprehensively considered the direct risk and potential risk of failures based on uncertain risk analysis theory and connection number theory, quantified uncertain correlation by the node degree and node clustering coefficient, then established a comprehensive risk indicator of failure. The proposed method has been proved by simulation on the actual power grid. Modeling a network according to the actual power grid, and verified the rationality of the proposed method.

1 Introduction
As the most complex artificial system, the dynamic behavior of the power system is affected by the structural and electrical properties. If just consider the electrical operation when dealing with catastrophic chain events, make it satisfy a series of strict constraints, such as the N-1 calibration criterion, then there will show vulnerability because of structure [1]. Therefore, in the evaluation of power grid security, domestic and foreign scholars have noticed that the complex coupling relationship between the structure and the electrical quantity has a profound impact on the operation of the power grid.

In the early literatures, the researcher just consider only consider the electrical properties, and studied the propagation mechanism of the dominant failure in the running state [2-3]. Until the researcher founded that the small average distance and the large clustering coefficient in the actual network topology are highly similar to those of the two parameters in the small world network [4-6]. And the degree distribution of nodes in a large number of real networks is governed by the scale-free power-law distribution [7-9], which is consistent with the scale-free effect. So far, the researchers have begun to pay attention to the impact of complex network properties in the grid structure on catastrophic events. At the same time, the direct risk but also potential risk should be considered. In Ref. [10], established the integrated risk index of cascading failures according to uncertain risk analysis theory [11,12] and connection number theory [13], but just considered extreme condition when determine the connection number.

Based on uncertain risk analysis theory and connection number theory, comprehensive considered the direct risk and potential risk of failures. Established a comprehensive risk indicator of failure, and determined the uncertain number by the node degree and node clustering coefficient. Then got a reasonable comprehensive risk assessment method of catastrophic accident. Considered the fact that the actual power grid is often with small world effect and scale-free effect, established Apollonian power grid which has both characteristics, and the validity and feasibility of the proposed method are verified by simulation.
2 Complex network properties and risk assessment

2.1 Comprehensive risk

Accurately assessing a series of risks caused by fault propagation is the basis for the assessment of catastrophic events in power grids. The inherent complexity of the macro structure of the power grid and the interval of the tolerance level of the micro components determine the risk after the failure, which will release a part of risk, but will remain a part of the risk of failure to release in grid. The former is expressed as the direct load loss and the loss due to component overrun. The latter is represented by the load loss resulting from the residual component overrun. So the former is called the direct risk, the latter known as the potential risk.

The direct risk can be represented as

\[ \text{Risk}_{\text{direct}} = \text{Cr}_i \times \left( \text{loss}_i + \sum_{j \in \text{over}} \left( \frac{\text{Cr}_j \times \text{loss}_j}{\sum_{j \in \text{over}} \text{Cr}_j} \right) \right) \]  

(1)

Where \( \text{Cr}_i \) is fault credibility measure of component \( i \), in the simulation of this paper, when the resistance interval coefficient \( \lambda \) of the set element is 1.1 times and 1.2 times, the corresponding component failure confidence measure is obtained by the limit value of the component operating state quantity in the literature [14]. \( \text{loss}_i \) is load loss of component \( i \), \( n \) is the number of over limited component cause by component \( i \) occur fault, \( \text{loss}_j \) is the loss of component \( j \) caused by component \( i \) occur fault. \( \text{Cr}_{ij} \) is fault credibility measure of component \( j \) after component \( i \) occur fault.

The potential risk can be represented as

\[ \text{Risk}_{\text{potential}} = \sum_{j \in \text{over}} \left( \text{Cr}_j \times \frac{\text{Cr}_{ij} \times \text{loss}_{ij}}{\sum_{j \in \text{over}} \text{Cr}_{ij}} \right) \]  

(2)

Where \( m \) is the number of over limited component after component \( i \) fault occur and further because component \( j \) fault occur. \( \text{Cr}_{ij} \) and \( \text{loss}_{ij} \) is the fault credibility measure and load loss of component \( r \), respectively.

The relationship between direct and potential risk varies with the path of the risk of failure, so it can not be dealt with directly in algebraic and simple ways. Therefore, we can use the idea of connection number [15] to establish a combination of comprehensive indicators that included uncertain factor, can be represented as

\[ \text{Risk}_{\text{total}} = \text{Risk}_{\text{direct}} \cdot \mu \cdot \text{Risk}_{\text{potential}} \]  

(3)

Where \( \text{Risk}_{\text{total}} \) is the comprehensive risk of component \( i \), \( \text{Risk}_{\text{direct}} \) is the direct risk, \( \text{Risk}_{\text{potential}} \) is the potential risk, \( \mu \) is the uncertain factor.

2.2 Calculating uncertain factor

In fact, the three basic attributes of complex networks are degree distribution, average shortest distance, and clustering coefficient. The degree of the node represents the number of edges connected to the node. The shortest distance between any two nodes refers to the minimum number of edges passing from one of the nodes to another node. The clustering coefficient of a node is defined as the proportion of the number of edges that actually exist to the maximum number of edges that may exist between \( k \) nodes that are directly adjacent to a node.

The development of catastrophic accidents in power grid can be divided into two stages: cumulative effect and chain effect [16, 17]. The cumulative effect in the stage of risk, the mathematical characteristics can be indicated that the potential risk of this layer is less than the comprehensive risk of the next layer fault triggered by it. And the comprehensive risk of this layer is greater than the comprehensive risk of the next layer fault triggered by it. Such as formula (4), (5).

\[ \text{Risk}_{\text{potential}} < \text{Risk}_{\text{total}} \]  

(4)
\[ \text{Risk}_{\text{total}_i} > \text{Risk}_{\text{total}_j} \]  \hspace{1cm} (5)

Where \( \text{Risk}_{\text{total}_i} \) is the comprehensive risk of component \( j \) due to component \( i \) occur fault.

The chain effect in the stage of risk, the mathematical characteristics can be indicated that the direct risk of this layer is less than the direct risk of the next layer fault triggered by it. And the comprehensive risk of this layer is less than the comprehensive risk of the next layer fault triggered by it. Such as formula (6), (7).

\[ \text{Risk}_{\text{direct}_i} < \text{Risk}_{\text{direct}_j} \]  \hspace{1cm} (6)

\[ \text{Risk}_{\text{total}_i} < \text{Risk}_{\text{total}_j} \]  \hspace{1cm} (7)

When the fault is still in the initial stage of the cumulative effect, if the degree of the two node between the faults is high, that is, the two nodes connected to more components, then the risk of fault can have more paths, more evenly shared out \(^{[18]}\). When the risk is further spread, if the two nodes have a higher clustering coefficient, then the risk of communication will be in this closely linked group within the region to better digest \(^{[19]}\), thus reducing the risk of further transmission, reducing the risk of the next layer of fault. With the development of the fault, when it has been developed to the chain effect stage, the higher node degree and the higher clustering coefficient will cause a larger range of component operation state change, leading to greater risk of fault. It can be seen that at different stages of the development of the chain fault, the node degree and the node clustering coefficient profoundly affect the behavior of the fault.

The node degree can represent the way risk can be shared, the clustering coefficient of the node characterizes the distribution of the risk that has been shared within the affected group area. And the impact of the two on the risk of failure is independent. In conclusion, when the fault is in the cumulative effect stage, the higher node degree and the higher node clustering coefficient help to suppress the risk of fault. When the fault is in the chain effect stage, the correlation degree and node degree and clustering coefficient is proportional, so the network of the largest node degree and the largest clustering coefficient corresponds to the most serious situation, so the normalization can be obtained after the cumulative effect stage and the chain effect stage as shown in (8), (9)

\[ \mu = \frac{C_{\text{min}} \times D_{\text{min}}}{C \times D} \]  \hspace{1cm} (8)

\[ \mu = \frac{C \times D}{C_{\text{max}} \times D_{\text{max}}} \]  \hspace{1cm} (9)

Where \( C_{\text{min}} \) is the minimum clustering coefficients of nodes in network. \( D_{\text{min}} \) is the minimum node degree. \( C_{\text{max}} \) is the maximum clustering coefficients of nodes in network. \( D_{\text{max}} \) is the maximum node degree. \( C \) is the average of the clustering coefficients of the nodes between the faults. \( D \) is the degree of the clustering coefficients of the nodes between the faults. Furthermore, can get the comprehensive risk of the cumulative effect stage and cascading effect stage, respectively.

\[ \text{Risk}_{\text{total}} = \text{Risk}_{\text{direct}} + \left( \frac{C_{\text{max}} \times D_{\text{max}}}{C \times D} \right) \text{Risk}_{\text{potential}} \]  \hspace{1cm} (10)

\[ \text{Risk}_{\text{total}} = \text{Risk}_{\text{direct}} + \left( \frac{C_{\text{max}} \times D_{\text{max}}}{C_{\text{min}} \times D_{\text{min}}} \right) \text{Risk}_{\text{potential}} \]  \hspace{1cm} (11)

2.3 Comprehensive risk assessment method

Based on the above principles, the power grid for catastrophic event dynamic comprehensive risk assessment process specific steps are as follows:

1. Carry out the initial power flow, and obtain the initial tolerance interval.
2. In the tolerance interval for the original tolerance interval 1 times, 1.1 times, 1.2 times, the N-1 fault is used as the initial event to randomly attack the grid, calculate the comprehensive risk of each failure event according to formula (10), and count the relationship between the comprehensive risk after each event and the proportion of the failed components.
3. According to the descending order of comprehensive risk of N-1 fault events, the first 50 groups
of fault events with the highest comprehensive risk are selected, and then the next layer of exposed components corresponding to each event is searched and the structural parameters are modified according to them.

(4) Based on the results of power flow calculation, obtain the credibility measure of the topology after the fault, calculate the direct risk of failure events according to formula (1), calculate the potential risk of failure events according to formula (2), calculate the comprehensive risk of failure events according to formula (3).

(5) Compare the risk of this layer fault event with the previous fault event, if the formula (4) and (5) are satisfied, the comprehensive risk of the fault event is calculated according to the formula (10), and the event is saved to the chain effect stage according to the principle of risk descending. If the formula (6) and (7) are satisfied, the comprehensive risk of the fault event is calculated according to the formula (11), and the event is saved to the cumulative effect stage according to the principle of risk descending. The first 50 groups of events with the highest comprehensive risk were selected from the fault of this layer, and the average comprehensive risk value was calculated and accumulated to the corresponding fault event. Count the relationship between the comprehensive risks after each event and the proportion of the failed components. (6) Determine whether the fault reliability measure of all network elements is less than a smaller positive value $\delta$. If that is yes, stop the simulation, otherwise to determine whether to reach the maximum number of search layers or the trend does not converge, and if that is yes, also end the simulation, otherwise go to step 4.

3 Simulation results

Established a network according to the actual power grid modeling in a western region, the 110 KV and above class substation is equivalent to the bus node, as shown in Fig 1. The network structure properties statistics, equivalent to a total of 40 nodes, 56 sides, the average degree of 2.8, the degree of node distribution in the interval $[1, 12]$, the node degree distribution shown in Figure 2. The distribution of node degree in the region has obvious power law distribution. Other network attribute statistics in the regional, and compared with the random network with the same number of nodes and average degree, the clustering coefficient greater than the random network, the average shortest distance smaller than the random network, which has the small world effect. To sum up, the regional power grid belongs to the small world effect and scale-free topology.

![Figure 1: An area power grid in west](image-url)
The catastrophic evaluation of the grid in this area is carried out by using the proposed method and the method of determining $\lambda$ in the literature [12]. The results of the cumulative effect stage and the chain effect stage are shown in Tables 1 and 2, respectively.

### Table 1: Risk ranking of cumulative effects stage

| Layers | Cumulative effect stage | Traditional method $\lambda=1$ | The proposed method |
|--------|--------------------------|---------------------------------|---------------------|
| 1      | $L_{2-12}, L_{32-38}, L_{12-38}, L_{32-40}, L_{12-15}, L_{37-38}, L_{2-8}, L_{37-38}, L_{12-16}, L_{2-4}$ | $L_{12-15}, L_{2-4}, L_{37-38}, L_{1-2}, L_{2-12}, L_{2-8}, L_{12-38}, L_{2-32}, L_{32-38}, L_{12-16}$ |
| 2      | $(L_{1-2}, L_{2-8}), (L_{1-2}, L_{2-4}) \quad (L_{2-8}, L_{2-4}), (L_{12-15}, L_{12-16}) \quad (L_{32-38}, L_{12-38}), (L_{2-8}, L_{2-4}) \quad (L_{12-16}, L_{12-38}), (L_{32-40}, L_{12-38}) \quad (L_{1-2}, L_{2-12})$ | $(L_{12-15}, L_{12-38}), (L_{12-16}, L_{12-38}) \quad (L_{1-2}, L_{2-8}), (L_{1-2}, L_{2-4}) \quad (L_{12-15}, L_{12-16}), (L_{12-16}) \quad (L_{2-4}, L_{2-12}) \quad (L_{12-38}, L_{37-38})$ |
| 3      | $(L_{1-2}, L_{2-4}, L_{2-8}), (L_{12-15}, L_{12-16}, L_{12-38}), (L_{32-40}, L_{32-38}, L_{12-38}), (L_{32-40}, L_{32-38}, L_{12-38}, L_{2-8}) \quad (L_{1-2}, L_{2-12}, L_{12-15}), (L_{1-2}, L_{2-12}, L_{12-16}), (L_{1-2}, L_{2-12}, L_{2-4}), (L_{32-38}, L_{12-38}, L_{12-13}), (L_{32-38}, L_{37-38}, L_{12-38})$ | $(L_{12-15}, L_{12-38}, L_{37-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}) \quad (L_{12-15}, L_{12-12}, L_{2-4}) \quad (L_{12-15}, L_{12-12}, L_{12-38}) \quad (L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-16}, L_{12-12}, L_{12-38}) \quad (L_{2-4}, L_{12-12}, L_{12-38}) \quad (L_{2-4}, L_{12-12}, L_{12-38})$ |

### Table 2: Risk ranking of cascade effects stage

| Layers | Chain effect stage | Traditional method $\lambda=1$ | The proposed method |
|--------|-------------------|---------------------------------|---------------------|
| 4      | $(L_{1-2}, L_{2-4}, L_{2-8}, L_{2-32}), (L_{32-40}, L_{32-38}, L_{12-38}, L_{12-15}) \quad (L_{32-40}, L_{32-38}, L_{12-38}, L_{12-16}) \quad (L_{32-40}, L_{32-38}, L_{12-38}, L_{12-16}, L_{12-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{12-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{12-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{12-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{12-38})$ | $(L_{12-15}, L_{12-38}, L_{37-38}) \quad (L_{12-15}, L_{12-15}, L_{12-38}) \quad (L_{12-15}, L_{12-15}, L_{12-38}) \quad (L_{12-15}, L_{12-15}, L_{12-38}) \quad (L_{12-15}, L_{12-15}, L_{12-38}) \quad (L_{12-15}, L_{12-15}, L_{12-38}) \quad (L_{12-15}, L_{12-15}, L_{12-38})$ |
| 5      | $(L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{12-15}) \quad (L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{12-15}) \quad (L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{12-38}) \quad (L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{32-38}) \quad (L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{12-16}) \quad (L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{12-16}) \quad (L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{12-16}) \quad (L_{1-2}, L_{2-4}, L_{2-8}, L_{12-12}, L_{12-16})$ | $(L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}) \quad (L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38})$ |
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term method.
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the larger clustering coefficient of the network can restrain the spread of the fault
catastrophic events. In this paper, the function established the influence mapping of the node clustering coefficient and the node degree in the different stages of the fault development in the network parameter, and has neither enlarged nor reduced the impact of potential risks on the grid. Therefore, in the traditional method N = 1 sort, some actual load is not large contact components $L_{2-12}$, $L_{3-38}$, $L_{12-38}$ and so on to the top, and this method proposed in this paper is a good balance between the direct risks and potential risks on the comprehensive impact of the grid, the $L_{12-15}$, $L_{2-4}$, $L_{3-38}$ has a large load, by the connection with the components of the key components of the relationship between the top row. It can be seen that there is no risk of potential risk in the cumulative effect stage of catastrophic event assessment, which accurately and reasonably assess the real impact of event direct risk and potential risk on the grid.

And then take the chain effect of the fault propagation to the 5th layer as an example, at this point the grid state has been very fragile, potential risks hidden in the grid at any time will occur avalanche. So in this condition, the traditional fixed coefficient method neglects the influence of the potential risk, and the proposed method establishes the influence mapping of the node clustering coefficient and the node degree in the different stages of the fault development in the network parameter, and has neither enlarged nor reduced the impact of potential risks on the grid.

Therefore, the fault sequence which make the network lose a large load and divide the grid into a series of islands such as $(L_{12-15}, L_{12-16}, L_{12-38}, L_{32-38}, L_{37-38})$, $(L_{12-15}, L_{12-16}, L_{12-38}, L_{32-40})$, $(L_{2-40}, L_{32-38}, L_{12-38}, L_{12-15}, L_{12-16})$, $(L_{12-12}, L_{12-38}, L_{32-38}, L_{37-38})$, $(L_{2-4}, L_{12-38}, L_{37-38}, L_{32-38})$ be ranked at the forefront in the proposed method. It can be seen that the results obtained by this method removed the too optimistic or too conservative part of the results of traditional method.

4 Conclusion
From the simulation results in Section 3, the rationality of the proposed method of describing connection degree $\mu$ is proved from the practical engineering point of view. The method proposed in this paper through the removal the defect that the evaluation results of the traditional methods are too optimistic and too conservative, the more accurate assessment of the real impact of the fault, and the assessment results more in line with the actual understanding of the project.

However, the improvement of electrical redundancy can not eliminate the inherent defects of power grid, it just can delay the occurrence of catastrophic events, and can not eliminate the occurrence of catastrophic events. So the operation of the dispatcher should make full use of the fault risk accumulation stage, the larger clustering coefficient of the network can restrain the spread of the fault and delay the entry into the catastrophe point of the cascading effect stage, and prevents the irreversible interlocking effect of the grid.

References
[1] Cao Yijia, Guo Jianbo, Mei Shengwei. System complexity theory for security evaluation of large power grid [M]. Beijing: Tsinghua University Press, 2010: 47-48, 50, 92-93.
[2] Overbye T J, Demarco C L. Voltage security enhancement using energy based sensitivities [J]. IEEE Transaction on Power Systems, 1991, 6(3): 1196-1202.
[3] Dobson I, Carreras B A, Lynch V E. Estimating failure propagation in models of cascading blackouts [C]. 8th International Conference on Probabilistic Methods Applied to Power Systems, Ames, USA, 2004: 641-646.
[4] MENG Zhongwei, LU Zongxiang, SONG Jingyan. Comparison analysis of the small-world topological model of Chinese and American power grids [J]. Automation of Electric Power System, 2004, 28(15): 21-24.
[5] DING Ming, HAN Pingping. Small world topological model based vulnerability assessment to large-scale power grid [J]. Proceedings of the CSEE, 2005, 25(supplements): 118-122.
[6] DING Ming, HAN Pingping. Small-world topological model based vulnerability assessment algorithm for large-scale power Grid [J]. Automation of Electric Power Systems, 2006, 30(8): 7-10.
[7] Barabasi AL, Albert R. Emergence of scaling in random networks [J]. Science, 1999, 286(5439): 509-512.
[8] Albert R, Albert I, Nakarado G L. Structural vulnerability of the North American power grid [J]. Physical Review E, 2004, 69(2): 1-6.
[9] Chassin D P, Posse C. Evaluating North American electric grid reliability using the Barabasi-Albert network model [J]. Physica A, 2005, 355(2-4): 667-677.
[10] Liu Runran. Study on several dynamic processes on complex networks[D]. Anhui: University Science and Technology of China, A dissertation for doctor’s degree, 2011, 6:10.
[11] Ding Lijie, Cao Yijia, Liu Meijun. Dynamic modeling and analysis on cascading failure of complex power grids [J]. Journal of Zhejiang University: Engineering Science, 2008, 42(4): 641-646.
[12] Feng Jing, Xiao Xian-yong, Cui Zhen. Small Probability Dynamic Risk Assessment of Power System Catastrophic Event Caused by Cascading Fault [J]. Power System Technology, 2011.
[13] Liu Baoding, Peng Jin. A Course in Uncertainty Theory [M]. Beijing: Tsinghua University Press, 2005: 75-78.
[14] Cui Zhen, Xiao Xianyong, Ma Chao. Assessment method of catastrophic accident in power system based on electric network dissection and uncertain measure [J]. Power System Protection and Control, 2011, 39(20): 30-37.
[15] Liu Baoding, Uncertainty Theory [M]. Beijing: Uncertainty Theory Laboratory, 2010, http://orsc.edu.cn/liu.
[16] U.S.-Canada Power System Outage Task Force. Final Report on the August 14, 2003 Blackout in the United States and Canada : Causes and Recommendations[R]. http://www.iwar.org.uk/cip/resources/blackout-03/.
[17] Ding Daoqi. Security analysis of large complex power grid-The concept and implementation of smart grid [M]. Beijing: China Electric Power Press, 2010: 123,127-130, 136-145,221-223, 293-294.
[18] Ning Xuanxi. Blocking flow theory and application [M]. Beijing: Science Press, 2005: 36-37.
[19] Bai Xiaoming, Zhang Boming. Reliability evaluation, early warning and decision support system for on - line operation of large - scale interconnected power [M].Beijing: Tsinghua University Press, 2010: 188-191.