Research on Optimization of Robustness for Cascading Failure in Power Grid

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Abstract. When considering the cascading failures or the robust performance of the power network, most of the researches in network science are based on the topology of the power network. However, according to some researches, only using the topology of the power network can not reasonably evaluate the robustness of the power network. Therefore, when considering the cascading failures in the power network, we must combine the electrical characteristics with the network topology to make a better evaluation. From the perspective of network science, the related research on cascading failures has made a lot of progress. In order to optimize the robustness of power network, the optimal topology of power network is designed under the cascading failure model combined with real electrical characteristics.

1. Introduction
In recent years, cascading failures in complex networks have been a hot topic [1]. When considering cascading failures or robust performance of power networks, the vast majority of research in network science is based on the analysis of network topology. However, according to some studies, only using the topological structure of the network can’t reasonably estimate the robustness of the real power network [2-6]. Therefore, when considering the cascading failure phenomenon in the power network, we must combine the electrical characteristics with the network topology to make a better evaluation. In the power system, researchers use the classical DC model [7] to calculate the power flow in the power network. The research work [8] uses the idea of for reference and integrates the DC model into the global load capacity cascading failure model to explore the cascading failure phenomenon in the power grid. However, the DC model has to face a problem in the process of cascading failure, that is, how to ensure the conservation of electric energy in case of failure. In order to solve this problem, unloading technology needs to be applied in every step of cascade failure iteration to ensure energy conservation.

The cascaded failure model used in this study is a new model proposed by Dr. Xi Zhang from Hong Kong University of technology [9]. In the model proposed by Xi Zhang, for the first time, the electrical characteristics of power grid are well integrated into the dynamic process of cascading failure. Because the previous models only consider the structure information of the network, this new model has attracted a lot of scholars' attention in the research of cascading failure based on the power grid. Among them, the nodes in the network are divided into four types according to the real power network scenario: power station node, consumer station node, relay station node and substation node. Next, the four kinds of nodes are introduced and described in detail.
2. Cascading Failure Model

2.1. The Admittance Model

Our model for the power system is based on the admittance model proposed. For a power system with buses, the model is written as

\[
A = \begin{bmatrix}
Y_{i_1} & \cdots & Y_{i_j} & \cdots & Y_{i_k} & Y_{i_h} & \cdots & Y_{i_m} \\
Y_{j_1} & \cdots & Y_{j_i} & \cdots & Y_{j_k} & Y_{j_h} & \cdots & Y_{j_n} \\
0 & \cdots & 0 & 0 & y_k & 0 & \cdots & 0 \\
Y_{h_1} & \cdots & Y_{h_i} & Y_{h_j} & Y_{h_k} & Y_{h_h} & \cdots & Y_{h_n}
\end{bmatrix},
B = [\cdots \ i_i \ v_k \ 0 \ \cdots]^T \quad (1)
\]

Subscript \(i\) denotes a consumer node (load); \(j\) denotes a distribution node; \(k\) denotes a generation node; \(h\) denotes a trans-former node. Given the power consumption, the generation information and the topology, the voltage of each node can be found using (6).

In this paper we introduce a more comprehensive model. Four kinds of nodes are considered in our model, namely, the generation node, the consumer node, the distribution node and the transformer node. We use the following power system equation:

\[A \cdot V = B \quad (2)\]

Then, the currents flowing in the transmission lines can be calculated as

\[I_{ij} = (v_i - v_j) \cdot Y_{ij} \quad (3)\]

Remarks: Equation (2) is derived from consideration of circuit laws and hence realistically describes the behavior of the power network. In our model, the generators are treated as voltage sources. The power emerging from generator nodes depends on their own voltages, the power consumption of other nodes and the network topology. Thus, the loads are balanced according to (2). In this model, we take the line current as the line load, the capacity of the line is \(1 + \alpha\) times of the initial line current, the load of the node is the load value of the node, and the capacity of the node is \(1 + \beta\) times of the initial load value. By attacking the connecting edge or node of the line as the initial fault, we calculate the line current and node power flow value to determine whether the overload, overload will remove the node or connecting edge, so as to simulate the propagation of cascading faults in power grid.

2.2. Robustness Parameters

In the field of power system analysis, the size of the outage size is measured by the size of the area not normally supplied. In this cascaded failure model with electrical characteristics, the robustness of the power network is measured by the total number of failed nodes in the network. Due to the removal of nodes or edges, the percentage of nodes not normally supplied in the stable network is defined as:

\[PUN(i) = \frac{N_{unserved}(i)}{N} \quad (4)\]

Where \(N_{unserved}(i)\) is the number of nodes that failed to function after the network reached a stable state due to a cascade failure caused by partial removal, and \(N\) is the total number of nodes in the network. According to the explanation of the cascade failure process, the nodes that failed to function in the network are either caused by an overload phenomenon or are not supplied with energy by a power station within the subnet in which the node is located. For nodes \(i\) or edges, if the corresponding \(PUN(i)\) value is larger, it means that this part has an important role in maintaining the robustness of the
network. When such nodes or edges are attacked, the robust performance of the network will encounter serious damage.

For a given power network, the objective to be optimized is the overall robust performance of the network, which is defined as

$$R = \frac{N}{L} \sum_{i=1}^{L} (1 - PUN(i))$$  \hspace{1cm} (5)

Among \(L\) is the total number of edges in the network. The physical meaning of \(R\) is the overall robustness of the network when the connected edges in the network are attacked. The attack on the connected edges is considered here because in many attacks on power networks, the attack on transmission cables is more common. In the absence of other explanations, the following robustness is calculated with this formula. The robustness of the network is closely related to the structure of the network. In order to explore the network topology under the optimal robustness, we construct the optimal topology design problem here:

$$\max R(G)$$  \hspace{1cm} (6)

Where \(G\) is Adjacency matrix of network. In order to solve this optimization problem, we use simulated annealing algorithm to get the approximate optimal solution.

2.3. Optimized Algorithm of Cross Reconnection Based on Degree-Preserving Edges

Figure 1 shows the structural adjustment method for degree-preserving edge intersection reconnection, and the degree of nodes in the structural adjustment process has not changed. The structural adjustment process for degree-preserving edge intersection reconnection is as follows:

1. Initiate the network, \(G_0, G'_0 = G_0\);
2. All connected edges are removed in turn for cascading fault simulation, and the fault scale after each removal is recorded, and the connected edge is restored until all connected edges have been removed, so as to obtain the robustness of the network \(R_0\);
3. Selecting the connected edge with the largest fault scale of \(G_0\), he vertices of the connected edge are node \(i\) and node \(j\) respectively;
4. Set the neighbor node set of the node \(i\) and the node \(j\) are \(G_i\) and \(G_j\);
5. Take one edge of the network \(G_0\) in turn, the vertex of the connected edge is node \(m\) and node \(n\) respectively, satisfy the node \(i \neq m, m \neq j, n \neq i\) and \(n \neq j\);
6. Deleting connecting edges \((i,j)\) and connecting edges \((m,n)\) in the network \(G_0\), respectively connecting the node \(i\) and the node \(n\), the node \(j\) and the node \(m\) to ensure network connectivity;
7. The method comprises the following steps that: the network \(G_0\) is subjected to cascading failure simulation of removing a connecting edge; the robustness \(R'_{new}\) of the network \(G'_{new}\) is obtained; whether \(R'_{new}\) is greater than \(R_0\) is judged; if so \(R'_{new}\) is assigned to \(R_0\) the network \(G_{new}=G_0\), \(G_{new}\) is assigned to replace the current optimal solution; otherwise, the current topology structure \(G_0\) and the robustness \(R_0\) are kept, and the next edge \((m,n)\) is re-selected in the step (5);
(8) Return the network \( G_0 = G'_0 \) to step (5) and re-select the next edge \((m, n)\) until the edge \((m, n)\) selection is completed;

(9) Network robustness \( R_{max} = R_0 \), the network \( G_0 = G_{new} \) to determine whether \( R_{max} \) is to remain unchanged, if so, the algorithm terminates, otherwise back to step (2), continue to execute the algorithm.

3. Simulation Analysis

In this simulation, we use IEEE14Bus to analyze the real power network. The network topology diagram of IEEE14Bus is shown in the figure 2, in which the total number of nodes is \( N = 14 \), the total number of edges is \( L = 20 \).

![IEEE14Bus network topology](image)

Figure 2. IEEE14Bus network topology, Red nodes are generator nodes.

The above experiments show that the robustness of the network is improved after the edge which leads to the largest cascading fault is protected by IEEE 14 networks, which also optimizes the network structure. So, if only one time of protected the degree of edge cross-reconnection, how to improve the robustness of the network, we use the following experiments to study.
Table 1. Size ordering of cascading failures caused by edge removal in IEEE 14 networks

| Serial Number | Connecting Edge | Cascading Failures Scale |
|---------------|-----------------|--------------------------|
| 1             | [3,4]           | 34                       |
| 2             | [2,4]           | 34                       |
| 16            | [12,13]         | 2                        |
| 19            | [1,2]           | 1                        |
| 20            | [2,3]           | 1                        |

In the IEEE14 network, the network cascading failures occur after the connecting edges are removed in turn, and the size of each network cascading failure is sorted.

When selecting the connecting edge which causes the least fault in the IEEE14 network, considering the restriction condition of the opposite edge, the edge 12-13 is selected.

Table 2. Connected Edge with Maximum Size Causing Cascade Faults and Connected Edge with Minimum Size Causing Guaranteed Edge Reconnection in IEEE14Bus Networks.

| Connecting Edge Selection | Original Network Robustness | New Network Robustness |
|---------------------------|-----------------------------|------------------------|
| 3-4                       | 9.485                       | 9.765                  |
| 12-13                     |                             |                        |

Table 3. Connected Edge with Maximum Size Causing Cascade Faults and Connected Edge with Minimum Size Causing Guaranteed Edge Reconnection in IEEE14Bus Networks.

| Connecting Edge Selection | Original Network Robustness | New Network Robustness |
|---------------------------|-----------------------------|------------------------|
| 2-4                       | 9.485                       | 9.835                  |
| 12-13                     |                             |                        |

4. Conclusion
In this paper, an algorithm of edge-degree-preserving cross-reconnection is proposed, which is applied to the cascaded fault model of power system. By studying the cascaded faults of IEEE14 network, and the connection edge is attacked as the initial fault of cascading fault, and the local optimal value of network robustness is obtained by carrying out multiple operations of edge-degree-preserving cross-reconnection on the connected edges which lead to the largest cascaded faults in the network. The structure of the network is optimized. On this basis, the characteristics between the largest fault causing edge and the smallest fault causing edge in the network are studied. The network robustness is improved by reconnecting the largest fault edge and the smallest fault edge only once. This further explains why the proposed algorithm can improve the network robustness by reconnecting the largest fault edge and the smallest fault edge.

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