Study on Cascading Failures of Power Grid Information Physics Fusion System Based on Pattern Search

Yue junying1,2, Li cunbin1

1 School of Economics and Management, North China Electric Power University, Beijing 102206, China
2 College of Computer Science and Technology, Inner Mongolia Normal University, Hohhot, 010022, China

*Corresponding author

Abstract. In a complex power grid, cascading failures that are triggered by some small disturbances can induce global catastrophic effects over the entire network. Based on the discussion of occurrence mechanism of power grid information physics fusion system cascading failures, this paper proposes an improved fault pattern search method. Compared with traditional search method, this method helps to improve the chain reaction set that causes the system failure, and makes it possible to make a comprehensive forecast search for grid link failures.

1. Introduction

With the advancement of smart grid construction and research, the application of communication and information technology in power systems will continue to expand. Power system has developed from traditional power equipment network into integrated information network and complex information physical fusion network system of electric power physical network. Multiple uncertainties and complexity in heterogeneous devices and heterogeneous networks present dual challenges to the stability and reliability of power systems.

In information physics fusion power system, the information layer and the physical layer depend on each other, and the information layer requires the energy supply of the physical layer grid nodes. Meanwhile, such complex correspondence relationship between two layers of networks makes the information physics fusion system more vulnerable to cascading failures.

Based on the discussion of occurrence mechanism of power grid information physics fusion system cascading failures, this paper proposes an improved fault pattern search method, to achieve a comprehensive forecast search for power grid cascading fault, and express the search results of cascading faults in form of tree structure accident chain.

2. Pattern Search Methods

Pattern search methods is to carry out fault simulation calculation on power grid through stochastic simulation, state space and analytic methods, so as to search out the failure mode that leads to grid fault. Among them, analytic method is based on deterministic criteria, such as N – 1 (or N - K) criterion, which is easy to understand and realize, but is not convenient for dealing with continuous parameters and uncertainties, and it is difficult to handle cascading failures or multiple faults. In order to avoid blind break selection, there is one solution that uses heuristic search methods. For example,
Koyama Y has proposed tie – cutting and Q – reduction index, by which can achieve selection of circuit and generator breaking, and then people could quickly search for cascading failure modes leading to voltage instability by simulation.

Stochastic simulation method is based on Monte Carlo Probability Sampling Algorithm. With Long enough simulation time, it can search all faults effectively. Some researchers have adopted this method to simulate the power system, and they calculated the overload effect of transmission line, the misoperation of protection and the probability of transient instability in the simulation process. However, the shortages of stochastic simulation method are: for the cascading failures based on time series, especially for long periods of protective action, there is lack of simulation in this method; the risk index is often expressed by probability expectation value, which is hard to understand; the calculation time is too long, so it is not suitable for online applications.

This paper proposes a noble pattern search method by combining the advantages of analytic method and stochastic simulation method, to achieve stability calculation and load flow calculation, and thus quickly and automatically filter out the cascading failure model that leads to serious consequences and prone to occur. Since cascading failure leading to major accidents is Small probability event, to conduct stochastic simulation through Monte Carlo Probability Sampling Algorithm cannot realize effect analysis, so we propose the cascading failure analysis method by combining state space analysis and network analysis.

3. Occurrence Mechanism of Power Grid Information Physics Fusion System Cascading Failures
Cascading failure is a continuous and complex dynamic process, usually caused by extremely rare serious accident, with certain contingency and predictability. The components involved in cascading failure not only include generator, transmission line, transformer, but also include bus, circuit breaker, disconnecting switch, voltage transformer, current transformer, etc. Bus fault, line fault, circuit breaker fault, maloperation and refusal of relay protection and sudden heavy load diversion are the major causes of cascading failures in the system. The difficulties in analyzing and simulating cascading failures lie in the diversity of triggering accidents and complexity of cascading processes. At present, people have some qualitative understanding of the mechanism of cascading failures.

Overload or fault tripping of transmission line would causes a great deal of load transfer, and thus leads to cascading tripping of a series of lines and power supplies, which is strongly related to major blackouts, especially cascading failures. Therefore, from the point of view of the load, the mechanism of cascading failure in power grid information physics fusion system is that: when the grid is running normally, each element has a certain initial load; when power grid fault occurs due to overload of one component or several components, the original trend of the system will change, and the load of the outage component is loaded onto the component that is still working; once these components cannot assume the new load and exit the run time, it will cause a new round of load distribution, which leads to interlocking overload, and eventually a large area of the network paralyzed and large-scale power outages may occur. If the initial fault occurs on a component with a large load, its adjacent components are likely to be unable to handle excess loads, so it is even more likely to cause cascading failures.

In order to better understand the development mechanism of cascading failures in power grid, some scholars have tried to build multiple models with pattern search, abstraction, simplification, reduction and statistics methods, to analyze the mechanism and behavior characteristics of cascading failures in power network. In recent years, some scholars are trying to explore new methods, models and analytical tools from complex system theory. They tend to regard the power grid as interaction system among individuals, and discussed network stability, vulnerability, disturbance propagation and control based on practical and ideal grid model, and then proposed a mathematical model for cascading failures. The load is one of the most important variables in the actual power system, and the load is strongly related to the load in cascading failures, so these models are particularly concerned with the load, which is the most important factor affecting the dynamic characteristics of power grids.
Another theoretical foundation of cascading failure modeling is complex network theory, complex network research belongs to the category of graph theory, which initially focused on planning, but significant changes in the size of the network force people to change the traditional analytical methods, and with the continuous increase in database capacity and computer storage and operational capacity enhancement, it becomes possible to explore the complex network containing tens of thousands of nodes.

4. Improved Fault Pattern Search Method
In order to achieve a comprehensive forecast search for grid cascading failures, and consider the possibility of various initial faults and the uncertainty of relay action as much as possible, this paper proposes a continuous self-healing fault search mode. Such method bases on ranking decision matrix of initial faults and ranking calculation method, to conduct search for cascading failures in power grids by constantly cycling. With constant loop search, it improves the search starting point through existing search results. In the search process, load flow and stability calculations are alternately carried out by numerical calculation procedures. After any initial failure and slip break, corresponding system stability judgment will be triggered. If the system is unstable, stop the current search; is it is stale, it can judge the next possible branch off according to the load flow calculation results. Similarly, current search loop will not stop until the end conditions are met, and then go to the next search cycle.

4.1 Sorting of Initial Faults
According to statistics, the development pattern of cascading failures in power grid is often due to a component fault in the system, and then cause a series of other components to stop. This paper mainly considers the initial faults in components including line, bus and transformer, to explore the cascading failure development model of grid information physics fusion system. The probability of failure of various components is different, so it first needs to construct the initial fault decision matrix to determine the order of the search. Moreover, the failure type of the initial fault has different influence on the development mode of grid cascading failure. Obviously, line initial failure of three-phase short circuit may produce more serious impact than single phase grounding, so we should set the corresponding weights for different fault types as: weight of three-phase short-circuit is \( w_1 \); weight of two-phase short-circuit is \( w_2 \); weight of two-phase short-circuit grounding is \( w_3 \); weight of single phase grounding is \( w_4 \); weight of other types of faults is \( w_5 \); and they meet constraints as follow:

\[
\sum_{i=1}^{5} w_i = 1
\]

The value of \( w_i \) can be determined based on expert experience or statistical data. If without support by expert experience or statistical data, we can also obtain its approximate value through repeated offline simulation calculation. Assume \( N_{\text{faults}} \) as total number of offline simulation, \( N_{\text{cascades}} \) as occurrences times of cascading failures, \( x_1, x_2, x_3, x_4, x_5 \) as the cascading failure times respectively caused by three-phase short-circuit fault, two-phase short-circuit fault, two-phase grounding short-circuit fault, single-phase grounding fault and other types of faults. The weights of above parameters can be obtained by formula as follow:

\[
W_i = \frac{x_i}{N_{\text{cascades}}} \quad i = 1, 2, \ldots, 5
\]

Assume there are N lines, M buses and K transformers in the system. To simplify the analysis, this paper only consider single failure, then the initial failure decision matrix is as Tab.1:

| Fault Type                  | Line 1 | Line 2 | Line 3 | … | Line N |
|----------------------------|--------|--------|--------|---|--------|
| three-phase short-circuit   | L_{11} | L_{12} | L_{13} | …| L_{1n} |
| two-phase short-circuit     | L_{21} | L_{22} | L_{23} | …| L_{2n} |
| two-phase grounding short-circuit | L_{31} | L_{32} | L_{33} | …| L_{3n} |
| single-phase grounding      | L_{41} | L_{42} | L_{43} | …| L_{4n} |
| other types of faults       | L_{51} | L_{52} | L_{53} | …| L_{5n} |
In the table, the element $L_{ij}$ can be expressed as:

$$L_{ij} = w_i \times P_{ij}$$  \hspace{1cm} (3)$$

$P_{ij}$ is the probability of $i$ type fault in line $j$. The value $L_j$ that line $j$ participate in the initial failure sorting is as:

$$L_j = \sum_{i=1}^{5} L_{ij}$$  \hspace{1cm} (4)$$

Similarly, the initial failure decision matrix of busbar and transformer can be obtained as Table 2 and Table 3:

| Tab.2. Initial failure decision matrix of busbar |
|-----------------------------------------------|
| three-phase short-circuit | Bus 1 | Bus 2 | Bus 3 | ... | Bus N |
| two-phase short-circuit | $B_{11}$ | $B_{12}$ | $B_{13}$ | ... | $B_{1n}$ |
| two-phase grounding short-circuit | $B_{21}$ | $B_{22}$ | $B_{23}$ | ... | $B_{2n}$ |
| single-phase grounding | $B_{31}$ | $B_{32}$ | $B_{33}$ | ... | $B_{3n}$ |
| other types of faults | $B_{41}$ | $B_{42}$ | $B_{43}$ | ... | $B_{4n}$ |

| Tab.3. Initial failure decision matrix of transformer |
|-----------------------------------------------|
| three-phase short-circuit | Transformer 1 | Transformer 2 | Transformer 3 | ... | Transformer N |
| two-phase short-circuit | $T_{11}$ | $T_{12}$ | $T_{13}$ | ... | $T_{1n}$ |
| two-phase grounding short-circuit | $T_{21}$ | $T_{22}$ | $T_{23}$ | ... | $T_{2n}$ |
| single-phase grounding | $T_{31}$ | $T_{32}$ | $T_{33}$ | ... | $T_{3n}$ |
| other types of faults | $T_{41}$ | $T_{42}$ | $T_{43}$ | ... | $T_{4n}$ |

The value $B_j$ that busbar $j$ participate in the initial failure sorting is as:

$$B_j = \sum_{i=1}^{5} B_{ij}$$  \hspace{1cm} (5)$$

The value $T_j$ that transformer $j$ participate in the initial failure sorting is as:

$$T_j = \sum_{i=1}^{5} T_{ij}$$  \hspace{1cm} (6)$$

4.2 Selecting Process of Initial Faults

After the initial fault decision matrix is constructed, and sorting of Initial failure probability of each component is determined, then we can obtain the value of $L_{ji}$, $B_j$ and $T_j$ according to formula (4)~(6), and then arrange them in order from large to small, and thus realize pattern search for cascading failures, until the search is complete. After the search process is over, the system records the cascading locus, marked as $A_{sel}$, to form a tree structured fault chain as follow:

$$A_{sel} = \left\{U_{i \in L_{cf}} L(i) \cup U_{i \in B_{cf}} B(j) \cup U_{i \in T_{cf}} T(k) \right\}$$  \hspace{1cm} (7)$$

In the formula, $L_{cf}$, $B_{cf}$, $T_{cf}$ are respectively the line set, busbar set and transformer set that have cascading failures; $L(i)$ is chain trip line; $B(j)$, $T(k)$ are the busbar and transformer that have cascading failure (i, j, k=1,2,...). Substituting the data of $L(i)$, $B(j)$, $T(k)$ into Tab.1~Tab.3 and Formula (4)~(6), and then obtain new $L_i$, $B_j$, $T_j$; search again, in such a reciprocating cycle.

After repeated searches, continuous correction is performed according to the results of search simulation, and the thresholds of line, bus, transformer failure to cause the cascading accident: $L_T$, $B_T$, $T_T$. Compare the calculated value of $L_i$, $B_j$, $T_j$ with the above thresholds. If the former value is not greater than the corresponding threshold, then it means the possibility that the initial fault may cause cascading failures is very small, so it is unnecessary to continue the search. The selecting process of initial faults is shown as Fig. 1.
4.3 Cascading Fault Search

After sorting of system component fault location, the search process will get started. Examine the protective action, reclosing and system stability status of the faulty component in turn. If the system has been unstable, then stop the search for the component and record the current search path; if the system is stable but the line broke, then continue to examine the protective action, reclosing and system stability status of surplus system. After multiple line breaking searches, if the system instability has not been searched yet, then set a maximum search depth $DP_{max}$ based on experience. If the search depth $d \geq DP_{max}$, and the system has not lost its stability, then calculate the related index, including total system outage load, disaster coefficient, user load loss coefficient and cascading loss coefficient, to determine whether the power system has a cascading reaction accident; if $d<DP_{max}$ and the system has not lost its stability, then continue to search.

This paper takes the total system outage load index as example. If the search depth $d>DP_{max}$, and the system has not lost its stability, then calculate the sum of load curtailment (SLC) in the accident path development process, marked as $P_{SLC}$:

$$P_{SLC} = \sum_{i \in N_{LC}} P_{LC}(i)$$  \hspace{1cm} (8)

In the formula, $N_{LC}$ is load cut node set; $P_{LC}(i)$ is the load shedding of each node. When $P_{SLC}$ is greater than empirical value, it can be assumed that a cascading reaction has occurred, which can be included in the accident set; if search depth $d>DP_{max}$, and $P_{SLC}$ is smaller than empirical value, then it can be assumed the cascading event model that start from the initial fault does not exist, so there is no need to establish a tree structured fault chain. The cascading fault search process is shown as Fig.2.
In the first search process, if there is no experience value or cannot determine the search depth, we can choose an appropriate value, and in subsequent cycle process, the value is corrected by a number of calculations. The protection action probability threshold can also be handled accordingly.

Acknowledgement
Fund Project: National Natural Science Foundation of China (71671065); State Grid Corporation of Science and Technology Project(5204BB1600CP)
References

[1] Yin S, Cagan J. An Extended Pattern Search Algorithm for Three-Dimensional Component Layout[J]. Journal of Mechanical Design, 2000, 122(1):102-108.
[2] Al-Sumait J S, Al-Othman A K, Sykulski J K. Application of pattern search method to power system valve-point economic load dispatch[J]. International Journal of Electrical Power & Energy Systems, 2007, 29(10):720-730.
[3] Wang J, Jiang C, Qian J. Robustness of interdependent networks with different link patterns against cascading failures[J]. Physica A Statistical Mechanics & Its Applications, 2014, 393(1):535-541.
[4] Zhou Z F, Xin A I, Deng H Q, et al. A Method to Analyze Power System Cascading Failure Based on Fault Tree and Fuzzy Reasoning[J]. Power System Technology, 2006, 30(8):86-91.
[5] Savla K, Como G, Dahleh M A. Robust Network Routing under Cascading Failures[J]. IEEE Transactions on Network Science & Engineering, 2014, 1(1):53-66.
[6] Fan W, Liu Z. An Overview on Modeling of Cascading Failures in Power Grids Based on Complex System[J]. Automation of Electric Power Systems, 2012, 36(16):124-131.
[7] Zhiyuan M A, Shi L, Yao L, et al. Study on the Modeling and Search Strategy of Event Chain for Cascading Failure in Power Grid[J]. Proceedings of the Csee, 2015, 35(13):3292-3302.