A novel searching method of fault chains for power system cascading outages based on quantitative analysis of dynamic interaction between system and components

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Abstract: Because the traditional searching method of fault chains for cascading outages usually only consider the overload protection or simulate the action of protection and control deterministically, a novel searching method of fault chains for power system cascading outages which is based on quantitative analysis of dynamic interaction between system and components is proposed. Based on fault chain model, an evaluating index is established. This index is used to quantize the action situation of protection and control of key elements. Furthermore, according to the index, the action probability of protection and control of key elements under critical condition is figured out to confirm subsequent events of fault chains for cascading outages. Finally, high risk fault chains are screened out based on the risk index. Taken some actual power system under the summer peak load condition in 2017 as an example, the simulation result proves reliability and effectiveness of the proposed method.

1. Introduction
In recent years, there have been many power system blackouts at home and abroad, such as blackouts in the United States and Canada in 2003, blackouts in Western Europe and blackouts in Italy; blackouts in Brazil in 2009 and 2011; two blackouts in India in the summer of 2012 [1]; and a blackout in Turkey on March 31, 2015 [2]. Although China has not experienced the above-mentioned serious blackouts, there have also been several local blackouts caused by cascading failures, such as the Central China Power Grid blackouts on July 1, 2006 [3]. These blackouts have a very serious impact on people's daily life and economy, and even threaten social stability.

The development of blackouts is a process of deterioration and intensification of power system operation, which starts with a small number of simple component failures and develops through a series of complex interruptions. Previous analysis shows that cascading failures often accompany the development of blackouts, and cascading failures play a role in boosting the occurrence of blackouts [4-5]. According to Murphy's law, if an event has the possibility of happening, although the possibility may be very low, it will happen in a certain situation. Similarly, although the occurrence of cascading failure blackout is a minimal probability event, once it occurs, the direct loss is huge, and the indirect loss is even more difficult to estimate [6]. Therefore, it is necessary to establish an appropriate cascading failure model, study the evolution mechanism of cascading failure and master the development law of cascading failure [7].

At present, there are many kinds of chain fault analysis models with different functions [8]. According to the different starting points of modeling, cascading failure analysis models of power system can be roughly divided into two categories: power flow/stability calculation based research
methods and network topology based research methods\textsuperscript{[9]}. Among them, the research methods based on power flow/stability calculation mainly include the related research on self-organizing criticality of complex systems and the search strategy of cascading failure modes\textsuperscript{[10]}. The research on self-organizing criticality of complex systems mainly includes OPA model and its improved model\textsuperscript{[11]-[12]}, hidden fault model \textsuperscript{[13]}, Manchester model \textsuperscript{[14]}, cascade fault model \textsuperscript{[15]} and branching process model \textsuperscript{[16]}. The research on pattern search strategy mainly includes fault tree analysis method and fault chain model \textsuperscript{[17]}. The research method based on network topology mainly uses complex network theory and combines the characteristics of power grid itself to study cascading failures of power grid from the overall point of view, and to seek the structural root of cascading failures \textsuperscript{[18]}. The model based on self-organizing criticality of complex systems can reveal the mechanism of cascading failures and quantify the risk of cascading failures, but it can not simulate the reaction mechanism of cascading failures in detail, and it is difficult to provide decision-making information for operators and planners. The development path and final results of cascading failures can be visually expressed by mode search strategy. Among them, the model of accident chain can not only simulate the reaction mechanism of cascading failure fail The study of macro-phenomena of large blackouts can also simulate the cascading failure response mechanism in detail, which provides an engineering application method for cascading failure control research, but its determination and calculation in subsequent links.

The key of cascading failure analysis based on accident chain is how to search for high-risk accident chain. Because of the large scale of power grid and the variety of accident inducements, the research focuses on how to improve the search speed of accident chain and search for the key links in the follow-up \textsuperscript{[20]-[21]}. Literature \textsuperscript{[22]} From the perspective of preventing major blackouts, a fuzzy comprehensive assessment method for cascading failure risk of power system based on accident chain is proposed. The method calculates the occurrence probability according to the quantitative evaluation value of the factors affecting the accident chain, and uses the severity index to evaluate the consequences of the accident chain from the perspective of system transient safety. Fuzzy comprehensive evaluation method is used to evaluate and classify the risk of accident chain, and the definition of risk level and the corresponding prevention and control guidance scheme are given. Literature \textsuperscript{[23]} proposes a prediction index of the intermediate link of the accident chain, which considers both the probability importance of the accident and the structural importance of the equipment in the network. The grey correlation degree algorithm based on maximum deviation is used to synthetically consider all kinds of indicators and construct a fault chain search model for cascading failures in power grids. The model based on complex network theory can analyze the overall system behavior \textsuperscript{[24]}, but it generally ignores the unique characteristics of power grid, such as electrical characteristics, operation characteristics and power flow characteristics, and is not fully applicable to the security and stability analysis and control of power grid.

In order to solve the problem that the traditional cascading failure chain search method can not take into account the uncertainty of protection control, this paper presents a method for identifying cascading failure chain in power system based on dynamic interactive quantitative analysis of system and components. This method is based on the accident chain model and considers the existing two or three protection configurations in the process of time domain simulation. The uncertainties of protection control are quantified by the action evaluation index of key component protection control, and the action probability of critical component protection control is calculated to determine the follow-up events of cascading failure chain. In addition, according to the action probability of protection control and its parameters, the following events of cascading failure chain are determined. The control cost after operation, the risk assessment of accident chain, and the screening of high-risk chain of cascading failures provide a reference for the prevention and control of cascading failures.

2. Accident Chain Theory

Accident chain theory originated from safety science and has been developed and applied at present. In many engineering fields. Accident Chain Theory in Electric Power System. Large blackouts are caused
by many intermediate links, and these are the main causes of blackouts. The intermediate link is not inevitable, but with the operation of the power grid. A series of factors, such as status, management and external factors, are related. Intermediate links are triggered, resulting in cascading failures. Defining the Set of Power Network Accident Chains and the Mathematical Table of Section k Accident Chains

Darwinian

\[ L = \{L_1, L_2, \ldots, L_n\} \quad (1) \]

\[ L_k = \{T_{i1}, T_{i2}, \ldots, T_{ilm}\} \quad (2) \]

In the formula: \( n \) is the number of power network accident chains; \( m_k \) is numbers of interlinks of accident chain \( L_k \); \( T_{il} \) is the link \( l \) in the accident chain \( k \), \( l=1,2,\ldots,m \). The logic represented by the above accident chain and the set of accident chains. The compilation relationship can be illustrated by the accident tree shown in Figure 1.

![Fig. 1 Logical relationship of fault chains](image)

The chain fault model based on accident chain provides a new control idea for the prevention and control of cascading failures. It only needs to cut off one or more links of the chain, instead of controlling all links, to prevent the occurrence of blackouts. The method of cutting off one or more links of the accident chain is to monitor the factors affecting the accident involved in this link, so as to avoid the failure of this link. According to this control idea, it is necessary to know the accident chain of power system beforehand. Therefore, how to quickly generate a reasonable accident chain has become the difficulty and focus of the theoretical model based on the accident chain.

3. Chain Search Model for Cascading Fault Based on Quantitative Analysis of Dynamic Interaction between System and Components

3.1 Protective Control Action Evaluation Index

There are two main criteria for the operation of protection or control devices in power systems: the first one can be described as \( (E, T_c) \), \( E \) is the threshold value of the electrical quantity of protection and control devices, and can generally be voltage, current, frequency and active power, etc. \( T_c \) is the allowable duration time, such as that of generators.

The second can be described as \( (Q,N) \), \( Q \) is an event, \( N \) is the threshold number of protection control actions, such as UHV continuous commutation failure blocking DC protection.

Time domain simulation can accurately simulate the action of protection and control devices and search the accident chain. However, it is difficult to consider some uncertain factors, especially the operation of protection and control in critical conditions, if the protection and automatic device can only be simulated with certainty.

In order to quantify the action of protection control, the two-dimensional criterion of protection control device action is expressed by one-dimensional index, that is, the evaluation index of key
component protection control action. The calculation formula is as follows. For the first protection control, its evaluation index is calculated as equation (3).

$$\lambda = \left[ E_i - (E_i - kT_i) \right] \times 100\% \quad (3)$$

Formula:

$E_i$ is the maximum/minimum electrical quantity monitored in the dynamic process (such as voltage, current, active power and frequency); $E_i$ and $T_i$ are the threshold value and allowable duration of the protection control device respectively; $k$ is the duration of electrical offset is converted into the conversion factor of electrical quantity.

When the values are different, the physical meanings are as follows:

$\lambda \geq 0$, indicating that the protective control device does not meet the operating conditions and is far from the operating boundary.

$\lambda = 0$ is close to 0, indicating that the protective control device is in a critical state of operation.

$\lambda < 0$, indicating that the protective control device meets the operating conditions.

For the second protection control, the evaluation index is calculated as follows.

$$\lambda = \frac{N-n}{N} \quad (4)$$

In the formula (4), $n$ is the number of actual actions; $N$ is the number of threshold set for protective actions.

According to the above analysis and the evaluation index of protection control action, the calculation formula of protection control action probability can be defined as follows.

$$P(\lambda) = \begin{cases} P & \lambda \leq 0 \\ P - \frac{\lambda}{\lambda_{ref}}(P - P) & 0 < \lambda \leq \lambda_{ref} \\ P & \lambda > \lambda_{ref} \end{cases} \quad (5)$$

In the formula (5), $\lambda$ is the index value of protection and control action evaluation and $\lambda_{ref}$ is the threshold value of ref are set for protection and control action evaluation, $P$ is the probability of hidden fault (when no hidden fault is considered, $P=0$), $P$ is the probability of correct action (when no hidden fault is considered $P=1$), $P$ and $P$ can be obtained by statistical data. Therefore, the relationship between the evaluation index of protective control action and its action probability is shown in Fig. 2.

![Fig. 2 Relationship between $\lambda$ and $P(\lambda)$](image)

### 3.2 Accident Chain Search Process

Combining with the evaluation index of key component protection control action, the proposed accident chain search process. The process shown in Figure 3 consists of the following steps:

1) According to the real-time operation data of power grid, the initial event sets are determined
based on expert experience, such as important main transformer N-1 and N-2 faults, key transmission line N-1 and N-2 faults and three-phase short-circuit single-phase rejection faults.

2) Starting from an event in the initial event set, the time domain simulation analysis is used to determine whether the load loss exceeds the set threshold. If it exceeds, it enters step 5 or step 3.

3) Judging whether there is a protective control action, if the action, the protective control action will be the next event, step 2, or step 4.

4) Calculate the evaluation index and the corresponding action probability of the key component protection control action. If the evaluation index of the key component protection control action is less than the set threshold value, the protection control with the minimum index value is selected.

Braking as the next event, go to step 2, otherwise go to step 5.

5) Calculate and judge whether the risk value of the current accident chain is greater than the set threshold value. If it is greater, save the accident chain and go to step 6, otherwise go directly to step 6.

If the current accident chain develops to m level, the formula for calculating the risk value of the accident chain is as follows

\[ R = \sum_{i=1}^{m} p(d_i|d_{i-1}, \ldots, d_1)C_i \]  

in formula (6) : \( p(d_i|d_{i-1}, \ldots, d_1) \) is conditional probability for the occurrence of level i events; \( C_i \) is control cost for Level I Events.

6) Judge whether the search of accident chain is over, if it is over, output the set of accident chains and end the method, otherwise step 1) Select the next initial event to continue the search of accident chain.

4. Analysis of three examples

4.1 Research subjects

In this paper, the planned grid structure of a practical power grid in 2017 is taken as the research object, and the high-risk cascading failure chain which may occur when different types of faults occur in the power grid under peak load in summer is analyzed.

4.2 Initial Fault Set

The initial fault set analyzed in this paper mainly includes the N-2 fault of 500 kV line in the actual power grid and the single-phase fault of 500 kV line with three-phase short circuit. The simulation analysis of all the initial faults shows that all the N-2 faults of 500 kV line can maintain the stability of the system, and the probability of cascading faults is very small. Therefore, cascading faults are not further analyzed. Three-phase short circuit single-phase malfunction of partial lines. In order to simplify the calculation, combined with the initial fault characteristics, the following line faults are selected as the initial fault concentration faults, as shown in Table 1.

| Accident sequence | chain               | Initial fault        | Initial Fault Occurrence |
|-------------------|--------------------|----------------------|--------------------------|
| 1                 | Liandu-Ouhai       | 0.001                |
| 2                 | Lithosphere-phoenix instrument | 0.001              |
| 3                 | Wuning-Danxi       | 0.001                |
| 4                 | Jinhua-Yongkang    | 0.001                |

4.3 Cascading Fault Chain Simulation

The threshold value of load loss is 30% of the total network load, the threshold value of protective control action index is 0.5, and the threshold value of accident chain risk is 10,000 yuan. Only the generation and load control costs are calculated, and the control cost of machine cut-off is 0.25 million yuan/MW, and the control cost of load cut-off is 10,000 yuan/MW. The simulation details are as
follows.

4.3.1 Accident Chain 1
The chain of cascading failures starts from the single-phase rejection fault of three-phase short circuit of Liandu-Ouhai line; after the failure, Binjin and Lingshao DC all fail to commutate continuously for three times (as shown in Fig. 3), the power is reduced by 15,000 MW; the bus positive sequence voltage of the two DC lines is shown in Fig. 4; after Lingshao and Binjin DC bipolar blocking, the frequency of the power grid continues to drop to 49.25 Hz (as shown in Fig. 5). As shown above, trigger the low frequency load shedding advance wheel action, the total load shedding is about 6200 MW. After the low frequency load shedding, the power grid frequency restores stability, the system reaches a new equilibrium point, and the cascading failure ends.

As shown in Figure 7, the risk of the chain of cascading failures is $99.5 million.
4.3.2 Accident Chain 2
Chain 2 of cascading faults starts from the single-phase rejection fault of three-phase short circuit of Cangyan-Fengyi line; after the faults, Lingshao DC continuous commutation fails three times, Binkin DC continuous commutation fails two times (as shown in Fig. 7), and the positive sequence voltage of the buses of the two DC lines is shown in Fig. 8.

According to formula (4) and formula (5), the evaluation index of Bingjin DC protection control action is 1/3 and the probability of bipolar blocking is 2/3. After Lingshao and Bingjin DC bipolar blocking, the total loss power is 15,000 MW, and the frequency of power grid continuously drops to 49.25 Hz (as shown in Figure 10), triggering low frequency load shedding ahead of time and reducing load totally about 6200 MW. After low frequency load shedding, the frequency of power grid restores stability. The system reaches a new equilibrium point and cascading failure ends (as shown in Figure 11). The risk of cascading failure chain is 726,000 yuan.

Similarly, accident chain 3 and accident chain 4 can be obtained by simulation. Their schematic diagrams are shown in figs. 12 and 13.

In addition, the appendix gives the simulation results of another high-risk cascading failure chain in the actual power grid, quantifying the key line low-voltage disconnection operation index and its operation probability by formula (3) and formula (5).
Fig. 8 Bus voltage of Ling-Shao and Bin-Jin DC lines

Fig. 9 Frequency curve of some generators

Lingshao DC continuous commutation failure 3 times latch-up and Binkin DC continuous commutation failure 2 times latch-up (Probability 2/3)

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Fig. 10 Schematic of high-risk cascading outage fault chain 2

Wuning-Danxi Three-Phase Short Circuit Single-Phase Rejection Fault

Binkin and Lingshao DC continuous commutation failure 2 times latch-up (Probability 4/9)

Low Frequency Load Shedding Advance Wheel Action

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Fig. 11 Schematic of high-risk cascading outage fault chain 3
4.3.3 Simulation results analysis

The simulation results of the chain of cascading failures mentioned above are analyzed and the following conclusions can be drawn:

1) Under typical operation mode, the single-phase fault of three-phase short circuit of 500 kV transmission line may lead to cascading failures with high risk, and the key events of high-risk cascading failure chain are Lingshao and Binkin DC bipolar blocking failures.

2) As shown in Fig. 6, the chain of cascading failures starts from the three-phase short-circuit single-phase rejection fault of Liandu-Ouhai line, experiences the failure of continuous commutation between Binkin and Lingshao DC, DC blocking, low frequency load shedding and finally reaches a new equilibrium point. From the search process of the accident chain, we can see that this method has the ability of traditional accident chain search. It can accurately simulate the deterministic action of protection control device and search the high-risk chain of cascading failures caused by the action of protection control.

3) As shown in Fig. 10, the chain of cascading faults starts from three-phase short-circuit single-phase rejection fault of Cangyan-Fengyi line, experiences three bipolar blockades of Lingshao DC continuous commutation failure, two bipolar blockades of Binkin DC continuous commutation failure, and the probability of bipolar blockade is 2/3. Load shedding at low frequency can finally reach a new equilibrium point. The analysis shows that, unlike the traditional simulation process which can not continue to search for follow-up events, the probability of the protection control device in critical state is calculated, so that the situation after the action is simulated in time domain, and the high-risk chain of accidents is searched. The search way of the chain of high-risk chain of cascading failures is increased, and the chain set of high-risk chain of cascading failures is completed.

5. Conclusions and Prospects

Based on the accident chain model and time domain simulation, combined with the actual operation conditions of the power grid and the configuration of the existing two or three lines of defense, and considering the interaction between the changes of the electrical quantity of the power grid and the protection control action, this paper proposes an evaluation index of the key component protection control action based on the dynamic interactive quantitative analysis of the system and the components. Through this index, the probability function of protection control action of key components is established, which can well simulate the uncertain action of protection control in critical state and increase the search path of chain of cascading failures. Based on risk index, chain of cascading failures with high risk can be searched, which can truly reflect the actual risk of large power grids, so as to guide the formulation of chain of cascading failures. Lock fault prevention and control strategy provides a certain research basis. By simulating a real power grid under peak load in summer of 2017, the effectiveness of the cascading failure chain search method proposed in this paper is verified.

The key component protection control action evaluation index proposed in this paper can be used...
to simulate most of the protection control action, but for some complex protection control (such as fan low voltage crossing) needs to be further studied. In addition, it is too simple to use linear function to simulate the action probability of protection control, which needs further study according to the actual situation.

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