RESEARCH ON INTELLIGENT TRUNCATION TECHNOLOGY OF SAFETY MARGIN STATE IN POWER OPERATION SYSTEM

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Abstract: The traditional safety margin state technology has low reliability in the case of continuous failure. By analyzing the influence of branch disconnection on node voltage and line load, the fault status events of safety margin components are screened. Then, according to the method of single circuit breaking, the overload circuit of power operation system is judged. And set the setting value of relaying protection, calculate the safety margin of component disconnection, and complete the intelligent truncation technology design of the safety margin state of power operation system. The n-3 fault state space is truncated, and the experimental results show that the intelligent truncation technology of power operation system safety margin state can effectively improve the reliability of the analysis results.

1. Introduction
In recent years, the power system has been developing towards the direction of ultra-high voltage, long-distance, large-capacity, cross-regional and ac/dc hybrid, which greatly improves the economy of the system operation, but also makes the safety and reliability of the power system operation gradually prominent, especially in recent major power outages abroad[1]. In the process of line over-load trip one after another, due to the dispatcher without analysis and decision support for evaluating the reliability of the event, unable to recognize the event severity and the degree of danger of the system, the lack of the concept of safety margin, don’t know how far is it from the safe and stable limit system, did not take timely measures to stable, system under multiple successive open circuit become fragile, finally develop blackout. The traditional safety margin state technology calculates the reliability by analyzing the safety of the power system, which can judge the abnormal operation situation after disturbance and carry out the breaking simulation of occasional events. However, the reliability of the analysis result in the case of continuous failure is low, and the state that endangers the system operation cannot be identified. In order to solve this problem, the intelligent truncation technology of the safety margin state of power operation system is proposed, which can analyze the system behavior after the accident and reduce the amount of calculation. On the other hand, the reliability of the system can be obtained by analyzing the previously neglected but harmful state of system operation.

Through the analysis of many power failure accidents, it is shown that every serious power failure in the past was almost caused by the failure of continuous line break. The trip of overload branch will cause the redistribution of system power flow, and its influence scope is global. However, in fact, the impact of branch trip on each transmission circuit is quite different. Only a small number of transmission circuits have sharply increased active power flow, and most of the transmission circuits...
have little or no change in active power flow. Based on this, starting from the idea of improving the preconceived accident evaluation and fault screening technology, this paper introduces the concept of node voltage over-limit and line over-load safety margin, and proposes the intelligent truncation technology of the safety margin state of power operation system by calculating the influence degree of the circuit breaking on the voltage of other nodes of the system and the line over-load. This technology can screen out the component fault state events with small safety margin after circuit breaking and conduct state behavior analysis, reduce the number of system states to be evaluated, and coordinate the contradiction between computing speed and accuracy. This algorithm will be helpful for the real-time evaluation of system reliability, especially for the event reliability analysis during the sequential circuit breaking.

2. Design of intelligent truncation technology for safety margin state of power operation system

2.1. Filter safety margin component fault status events

Considering that there are many line faults in the actual power system, it is necessary to screen the fault state events of safety margin components first. Markov equation is a commonly used risk assessment algorithm, and let \( \{ x(t), t \geq 0 \} \) be a random process taking the value of \( E = \{0,1,\ldots,n\} \). If there is \( i_1, i_2, \ldots, i_n \in E \) for any natural number \( n \) and any time point \( 0 \leq t_1 < t_2 < t_3 < \ldots < t_n \), then \( \{ x(t), t \geq 0 \} \) is the continuous time markov process on the discrete state space. And if for any \( t, u \geq 0 \), all have \( p\{X(t+u) = p_y(t)\} \) for the fixed \( i, j \in E \), the function \( p_y(t) \) is the transition probability function. \( p(t) = p_y(t) \) is called the transition probability matrix. The transition probability functions of markov process \( \{ x(t), t \geq 0 \} \) all satisfy \( p_y(t) \):

\[
\lim_{t \to 0} p_y(t) = \delta_{ij} = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases}
\]

Where, \( p_y \) represents failure efficiency and \( t \) represents repair rate. The average unavailability rate in the long-term cycle of components is shown in the formula.

\[
U = \frac{\lambda}{\lambda + \mu} = \frac{f \times \text{mtr}}{8760}
\]

Where, \( \lambda \) represents the average repair time, \( \mu \) represents the average time before failure, and \( f \) represents the average failure frequency.

Since markov equations are based on state space diagrams, they are sometimes called state space methods. The advantage of this approach is that all states and their transitions have a clear graphical representation. Therefore, markov state equation is applicable to the component shutdown model of power operation system. In the power operation system, the shutdown model of system components can usually be divided into independent shutdown and related shutdown, and the safety margin component fault state event process can be screened, as shown in figure 1.
When generating the initial population, random function can be used to randomly set the switch state that needs to participate in the coding into an open or closed state, and random Numbers will be taken as many times as there are many individuals in the population\(^5\). As the maximum safety margin of regional power grid is the fitness function, it determines the ordering of search direction by genetic algorithm. Therefore, in the calculation process, the fitness function value corresponding to each generation of individuals is calculated by using the ranking function. At the same time, it is arranged in the order from large to small, so as to obtain the ranking of the advantages and disadvantages of the generation of individuals. The larger the fitness function value is, the higher the safety margin value will be. After several generations of optimization calculation, the global optimal solution can be obtained after the convergence condition or the evolutionary algebraic condition is satisfied. The open and closed state of the contact switch in the regional power network corresponding to the solution determines the network structure with the maximum regional power network safety margin.

2.2 Identify overloaded lines in power operation systems

Any branch \( I_y \) break can be processed by superimposing the two networks in figure 1(a) and (b). FIG. 1(a) shows the basic operation, while FIG. 1(b) shows the operation when only \( \Delta I_i = I_y \) and \( \Delta I_i - I_y \) act on branch \( I_y \)'s disconnected network, as shown in FIG. 2.
It can be seen that for the analysis and calculation of branch \( I_{ij} \) disconnection, only the node voltage \( \Delta v \) generated by \( \Delta I_i \) and \( \Delta I_j \) in (b) network can be calculated\(^6\). For (b), the network has \( \Delta v = z' \Delta I \), where, \( \Delta I = [0...\Delta I_i...\Delta I_{ij}...0]^T \); \( z' \) is the node impedance matrix after branch \( I_{ij} \) is broken. According to equation (3), the voltage increment of any node \( K \) after branch \( I_{ij} \) is broken can be obtained, and the calculation formula is:

\[
\Delta v_k = z' \Delta I_j + z'_{ij} \Delta I_j \tag{3}
\]

Branch \( I_{ij} \) breaking is equivalent to adding a branch with \( z'_{ij} \) impedance between \( i \) 、 \( j \) nodes, Therefore, the relation between \( z'_{ij} \) and \( z_{ij} \) and the element of the original node impedance matrix before branch breaking can be obtained by branch addition method as

\[
z'_{ij} = z_{ij} + \left( z_{ij} - z_{ij} \right) \left( z_{ij} - z_{ij} \right) \quad z_{ij} \quad z_{ij} \quad \text{represents the active power flow, and} \quad z_{jj} \quad \text{represents the number of nodes.}
\]

By substituting equations (3) and (4) above into equation (2), the voltage increment of each node of the power network can be obtained after branch \( I_{ij} \) is switched on. Accurate calculation of active power flow of branch I after circuit opening and breaking. In practical engineering application, in order to effectively prevent chain overload, quickly view the whole situation, and perform online real-time emergency security analysis. To determine whether the removal of an overloaded line will cause further overload of other lines, an imprecise calculation can be adopted. For the need of online analysis and calculation speed, an analysis model of single line overload is presented\(^7\). This model is based on the dc power flow distribution coefficient method, which can directly calculate the power increment of each branch in the system without solving the network equation. The calculation speed is fast, which is suitable for safety and rapid analysis under emergency conditions. When there are multiple lines, the analysis can be conducted according to the method of single line breaking to identify overloaded lines in the power operation system\(^8\).

2.3 Safety margin calculation for component disconnection

When the circuit and other components are disconnected, the voltage of some nodes in the system will exceed the limit or the line will be over-loaded. In the theoretical calculation of system power flow after disconnection, the node voltage and branch load must meet the following power flow constraint

\[
V_{\min} \leq V_{k} \leq V_{\max} .
\]

However, in practical engineering, in order to ensure the normal operation of the
system after component disconnection and effectively prevent the system from large-scale power failure caused by the chain overload of successively broken lines, the node voltage and line load of the power department usually have a certain margin, and the corresponding setting value of relay protection is set to prevent accidents\[9\]. Therefore, this paper introduces the concept of node voltage and line load safety margin.

Node voltage safety margin: refers to the allowable variation range of node voltage in order to ensure the safe operation of the system under various circumstances, which is expressed by $\lambda^v_k$. The calculation formula is as follows:

$$\lambda^v_k = \min\left(\frac{V_{k,\text{max}}}{V^k}, \frac{V_k}{V_{k,\text{max}}}\right)$$ (4)

Where, the size of $\lambda^v_k$ depends on the situation of the nodes. In normal operation, the voltage of each node of the system is strictly limited within the constraint range or even smaller than the constraint range, then $\lambda^v_k \geq 1$; Of course, some nodes are also allowed to run for a short time without satisfying the voltage constraint\[10\].

Safety margin of branch load: refers to the allowable load of the branch in order to ensure the safe operation of the system under various circumstances, represented by $\lambda^p_k$, also known as the branch load coefficient, and the calculation formula is as follows:

$$\lambda^p_k = \frac{p_{j,\text{max}}}{p_j + \Delta p_j}$$ (5)

In normal operation, the value of branch $\lambda^p_k \geq 1$ is affected by the thermal limit of the line and other factors\[11\]. $\lambda^p_k < 1$ is the over-load operation of the line, and its size indicates the degree of over-load. In order to ensure the safety of the line, there must be a certain load safety margin.

The algorithm is to select the safety margin is small, disconnect between the influence degree of component is larger or do have broken system fault state to calculate the system reliability index\[12\], not to consider those affected or not easy to have open circuit state, reduce the number of need analysis of the system fault state, improve the reliability of analysis results.

3. Experimental analysis

In this paper, the intelligent truncation technology of safety margin state of power operation system and the traditional safety margin state technology are compared and analyzed on the Windows platform. The system consists of 22 500 kV substations, 45 ac transmission lines and 3 dc systems, and its system wiring diagram, system operation mode, component parameters, component number and reliability equivalent block diagram, etc. In the analysis of the main network system, the application of the system state space truncation based on the node voltage and line load safety margin after component disconnection in the system reliability analysis under the condition of multiple faults and the type of multiple faults are illustrated by taking multiple faults as an example.

System n-3 failure: a system in which three components fail. The method in this paper is used to calculate the node voltage and line load safety margin after the main network component is disconnected, and the system state truncation is carried out. The experiment is carried out according to 11 indicators, as shown in table 1.

| Disconnect branch $i$ | Node voltage safety margin | Branch $i, j$ |
|----------------------|---------------------------|---------------|
| L 9                  | $\lambda^v_{10} = 0.835$ | L 9-10        |
| L 47                 | $\lambda^v_{44} = 0.859$ | L 30-18       |


The n-3 fault state space of the system is truncated, and the number of fault states to be evaluated varies with the size of the pre-set truncation value. In this paper, the fault state space of the truncated system of line load safety margin is illustrated by an example. By calculating the n-3 fault lambda matrix of the system and setting different values, the trend curve of the number of state changes after truncation by the two methods is shown in figure 3 and 4.

| L 30 | $\lambda_{28} = 0.846$ | L 47-30 |
| L 9  | $\lambda_{9} = 0.849$ | L 9-47  |
| L 18 | $\lambda_{30} = 0.855$ | L 9-29  |
| L 29 | $\lambda_{g} = 0.858$ | L 29-30 |
| L 42 | $\lambda_{45} = 0.855$ | L 9-18  |
| L 12 | $\lambda_{29} = 0.859$ | L 47-12 |
| L 12 | $\lambda_{41} = 0.859$ | L 47-29 |
| L 34 | $\lambda_{40} = 0.859$ | L 30-34 |

Figure 3. Intelligent truncation technology for safety margin status of power operation system

Figure 4. Traditional safety margin state technique

FIG. 3 and FIG. 4 are the experimental results. It can be seen from FIG. 2 that the intelligent truncation technology of the safety margin state of the power operation system can truncate the fault state of the system. Within a certain range, the number of system fault states and analysis time vary greatly with the truncation value. The smaller the truncation value, the fewer the number of system fault states after truncation and the less the calculation time. When the truncation value is greater than 50, some states affecting the line may also be considered as a fault state of the system. In the actual system analysis, generally only the over-load state of the line needs to be considered. Of course, the technology in this paper can also take into account the heavy load state of the line. According to the
analysis in figure 3, if the n-3 safety criterion is directly adopted to determine the level 3 faults of the system, the number of possible faults is very large and the amount of calculation is very large, among which only a few combination cases are helpful for the operation of the analysis system, and the calculation amount can be reduced by adopting the method in this paper. The calculation results show that the traditional safety margin state technology is seriously affected by the branch coverage, which is consistent with the analysis results of widespread blackout accidents. Although the impact of open circuit branch location related because associated with the network structure of concrete, but generally not more than 20% of the total system transmission branch, in the event of a power transmission device is overloaded, the dispatcher just estimate overload branch off to this part of the line, the influence of relative entire network communication trend analysis, improve the reliability of the results of the analysis.

4. Conclusions
This paper analyzes the voltage of system node and the over-load of the line after the components are disconnected. The reliability evaluation reflects the weakness of the power system. Finally, the key information is provided to improve the reliability of power grid operation through experiments, and some Suggestions are given to the actual operators. The intelligent truncation technology of the safety margin state of power operation system can improve the reliability of the analysis results, but has little influence on the reliability index. It is hoped that in the following research, improvement will be made to pave the way for the real-time evaluation of power reliability.

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