ARCHIVES OF ELECTRICAL ENGINEERING VOL. 69(3), pp. 661–677 (2020)

DOI 10.24425/aee.2020.133924

Research on optimal configuration of fault current limiter based on reliability in large power network

Jianjun Zeng, **Yonggao Zhang**

School of Electrical and Automation Engineering, East China Jiaotong University
China
e-mails: zhaohy1978321@yeah.net, ygzhang@ecjtu.jx.cn

(Received: 29.11.2019, revised: 15.04.2020)

Abstract: With the availability of UHV engineering technology, the scale of the power network is expanding, and the level of the short-circuit current is getting higher, which brings hidden trouble to the safe and stable operation of the power network. Further this article issued a method that optimized the configuration of a current limiter based on the reliability of the power network. According to the reliability analysis under the influence of a short circuit, the quantitative evaluation of reliability of the power network is realized by the calculation of the short-circuit current. A quantitative model is established among reliability evaluation and the short-circuit current as well as load loss, the candidate installation site of a current limiter can be determined according to reliability quantification results. This method uses the particle swarm optimization algorithm to optimize the distribution of the limiter, aiming at the reliability level and the minimum number of current limiters in the short circuit of a power grid. Finally, taking the actual power grid of a province as an example, the result shows that this method can reduce the search space of the optimal solution, optimize the configuration of the current limiter, and effectively limit the short-circuit current and improve the reliability of the power network.

Key words: configuration optimization, fault current limiter, reliability, short circuit current

1. Introduction

With the continuous development and expansion of the power grid in China, it is gradually forming a UHV-based power grid as the backbone. The large scale, long transmission distance and large transmission capacity of the ultra-high voltage (UHV) power grid lead to the rapid increase of the short-circuit current in this grid, which has numerous consequences.

Therefore, the over-standard short-circuit current affects the safety and the stability of the UHV power grid directly, and becomes one of the urgent problems to be solved in the development of UHV.

At present, in view of the problem of the short-circuit current exceeding the limit of a power grid, a variety of current limiting measures have been proposed, and mainly divided into two kinds. One is to change the operation mode of the system by adjusting the structure of the power grid. For example, in reference [1–3], based on the sensitivity weighting and fitness function of transfer impedance, a mathematical model of line-breaking grid adjustment is proposed, which forms global optimization algorithms for fast calculation of grid adjustment to limit the short-circuit current. The other way is to control the short-circuit current by adding a fault current limiter. Reference [4, 5] establishes a model with the objective function of network loss and economic cost, and realizes the optimal configuration of a fault current limiter. Reference [6–8] establish a model based on the change of the short-circuit current and branch impedance sensitivity, and combines the algorithm to optimize the distribution of current limiters. In reference [9], a particle swarm optimization (PSO) model is proposed to minimize the number of electric reactors and the total impedance.

The above algorithm model mainly considers the impedance changes before and after installing the current limiter. Although it can effectively reduce the optimized search range, the search efficiency is low in the actual large power grid. At present, the research focuses on the analysis model, sensitivity, loss and economics of fault current limitation. The current limiting measure can achieve better current limiting effect when the reliability level of all equipment in the power grid is high. However, in actual grid operation, the reliability of different equipment is different. This paper proposes a fault current-limiting analysis that considers reliability, which is an effective supplement to the current research. From another point of view the research wants to ensure the safe and stable operation of a power grid after a short-circuit.

Dynamic reliability is the primary prerequisite for grid operation, after a short circuit occurs, the current rises sharply, and equipment with a low level of reliability in the power grid may also cause new faults that spread further, eventually causing a cascading breakdown. Therefore, the dynamic reliability evaluation of the grid is very important in the case of a short circuit. At present, most schemes about short-circuit current limitation does not consider the reliability of the grid before and after the installation of the fault current limiter. Furthermore, although the above model performs the arrangement of the flow restrictor for the optimal installation of the current limiter, there are certain problems for the stable and reliable operation after installation that have not been checked yet. Finally, the existing research on the installation of the current limiter is generally considering all lines of a large power grid, the calculation amount is large, and there is some uncertainty. Therefore, how to simplify the solution to install the minimum current limiter into the large power grid while ensuring the reliable and safe operation of the power grid is the key to solving the problem.

In summary, this paper starts from the impact of the short-circuit current exceeding the standard on the dynamic reliability of the power grid. Through the analysis and evaluation of the reliability of the power grid structure, a simple mathematical model based on the need to solve a short-circuit problem is obtained. The paper establishes models and algorithms based on reliability analysis to simplify the network structure and reduce the scope of the limiter search. The optimal configuration of the reliability of a basic upper limiter is realized, the operational reliability level after the short circuit of the power grid is improved, and the hidden danger of the fault diffusion after the short circuit is eliminated. Finally, taking the actual power grid of the selected province as an example, the feasibility of this scheme is verified.

2. Short circuit analysis after UHV

2.1. Short-circuit current of the grid frame after UHV connection

UHV has great advantages in large-capacity long-distance transmission as well as has the characteristics of providing transportation capacity, saving land resources and reducing transmission loss. However, the short-circuit current usually makes changes after it occurs in the UHV power grid. In large power grids, without considering the impedance of a short-circuit branch, the formula for calculating the short-circuit current of any node is as follows:

$$\dot{I}_k = \frac{\dot{U}_k}{Z_{kk}}, \tag{1}$$

where, Z_{kk} is the element of node impedance matrix. $\dot{U}_k$ is the voltage of node k before failure.

Firstly, after the UHV access, the electrical distance between the regional grids is closer, the electrical distance is shortened, and the system impedance is relatively reduced [10, 11]. Secondly, the interconnection between the provincial grids makes the overall system larger. Finally, in the initial stage of UHV construction, an electromagnetic loop network will be formed between UHV and 500 kV power grids, it will cause the short-circuit current of the UHV access point to increase sharply. Take the example of some provincial power grid that is planned to be connected to UHV, Fig. 1 shows the planning grid structure of a provincial power grid after it is planned to be connected to UHV.

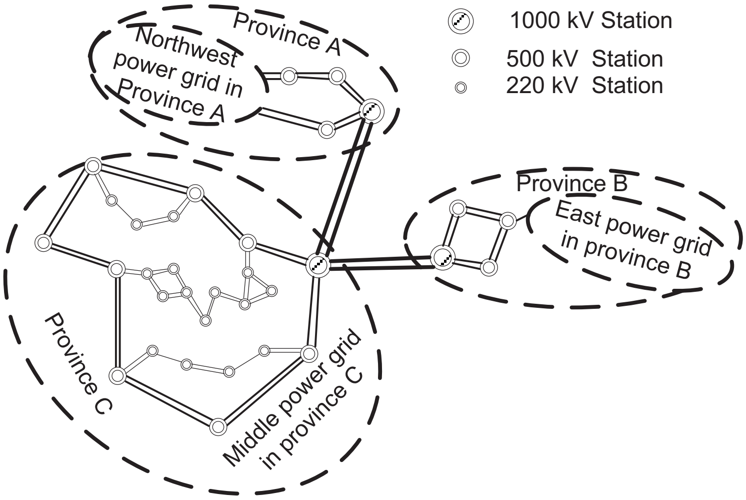


Fig. 1. Planning grid structure after ultra-high voltage access in some province

By analyzing the planning grid structure shown in Fig. 1, the conclusion is that the voltage level is increased, the electrical distance is shortened, and the tightness of the electromagnetic ring network formed by the UHV will make the equivalent contact impedance smaller after the UHV is connected. It will lead to a sharp increase in the short-circuit current. Table 1 shows the increase in the short-circuit current before and after the UHV access.

Table 1 shows that the short-circuit current of the bus bar near the falling point exhibits a certain degree of increase, and the increase of the short-circuit current of the most bus bars is higher than 20%, and even in some bus bars it is increased by 50% after the UHV is connected. Therefore, it is necessary to calculate the short-circuit current of the planned grid and take corresponding measures to meet the requirements of safe and stable operation of the system after UHV access in order to carry out the construction of UHV projects in practice.

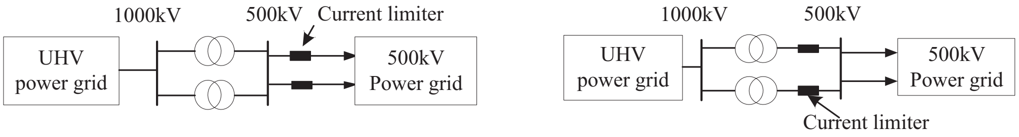
Table 1. Short-circuit current of some bus lines before and after UHV access in some province

Bus name	**Three-phase short-circuit current (kA)**		**Relative growth**
	Before UHV connection	**After UHV connection**	
CS	31.352	46.375	47.9%
DX	40.491	48.39	19.5%
DM	40.413	51.799	28.2%
JX	41.974	67.379	60.5%
QG	37.052	49.192	32.8%
WG	38.975	54.493	39.8%
KMJ	45.775	60.003	31.1%
LF	47.16	59.082	25.3%
YC	32.797	51.662	57.5%

2.2. Short circuit of current limiter

At present, there are many measurements regarding current limitation. In the 220 kV voltage side, unwinding the electromagnetic ring network can be used to limit the short-circuit current, and installing the current limiter can also be adopted. However, in the 500 kV side grid, the current limiter can be used to limit the short-circuit current, because it has less impact on the power grid. The installation current limiter scheme has mainly the following two types, which can be seen in [12]. In the first one, it is installed on the UHV 500 kV outlet line. In the second one, it is installed at the 500 kV outlet of the UHV main transformer. Another way is to limit the short-circuit current at the 500 kV bus bar, which is provided by the UHV system. Fig. 2 shows the different installation location of the current limiter.

Combined with the analysis of Fig. 1 and Fig. 2, the grids with different voltage levels have different limiting effects when the current limiter is installed. Due to current development and economic problems, the current limiter for 220 kV is economically superior. However, due to



(a) Installed on 500 kV outgoing line (b) Installed on 500 kV main transformer

Fig. 2. Position of the current limiter for 500 kV network

a large number of lines with this voltage level, the idea of current distribution is basically related to a 500 kV station. In order to limit the short-circuit current of each line effectively, it needs much more current limiters installed, thus the grid structure becomes more complicated. For the current limitation problem of 500 kV high voltage level, although the cost of the current limiter is relatively higher, the installation quantity is relatively smaller, and the short-circuit current of the low level of the peripheral voltage can be effectively limited.

According to the literature [12] and the analysis of short-circuit calculation, it is a simplification to consider a fault current limiter installation in series as the parallel problem. The impedance of the current limiter under fault is Z_{FCL}, equivalent to the parallel one branch Z_F, with the original impedance number of matrix nodes in the initial state, which is shown in Fig. 3.

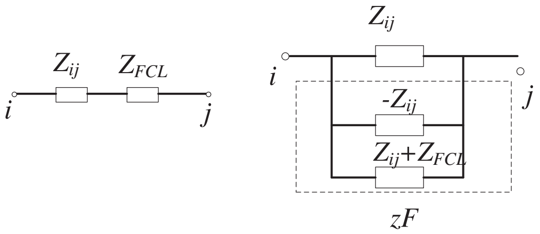


Fig. 3. The equivalent circuit after adding the current limiter

The node admittance matrix is analyzed and calculated by the branch addition method. The magnitude of its impedance is:

$$Z_F = (-Z_{ij})//(Z_{ij} + Z_{FCL}) = \frac{-Z_{ij}(Z_{ij} + Z_{FCL})}{Z_{FCL}} . \tag{2}$$

The change of the diagonal elements of the impedance matrix after installing the fault current limiter is:

$$Z'_{kk} = Z_{kk} - \frac{(Z_{ki} - Z_{kj})^2}{Z_{ii} + Z_{jj} - 2Z_{ij} + Z_F} . \tag{3}$$

The change of self-impedance is:

$$\Delta Z_{kk} = \frac{(Z_{ki} - Z_{kj})^2}{Z_{ii} + Z_{jj} - 2Z_{ij} + Z_F} = \frac{C_1^2}{C_2 + Z_F} , \tag{4}$$

where,

$$C_1 = Z_{ki} - Z_{kj}\,,$$
$$C_2 = Z_{ii} + Z_{jj} - 2Z_{ij}\,.$$

When a short-circuit fault occurs in the system, the condition in which the branch *ij* upper limiter can be reliably started, is the current flowing through the branch greater than 3.5 times the normal current. At this time, the current limitation effect of the installed current limiter installation on the over-standard site k is represented by the symbol λ_k, which can be expressed by (5).

$$\lambda_k = \frac{I_k - I_k'}{I_k} = \frac{\left(\dfrac{U_k}{Z_{kk}} - \dfrac{U_k}{Z_{kk}'}\right)}{\left(\dfrac{U_k}{Z_{kk}}\right)} = \frac{Z_{kk}' - Z_{kk}}{Z_{kk}'} = \frac{\Delta Z_{kk}}{Z_{kk}'}\,. \tag{5}$$

The upper limit of the current limitation level of the whole network system is I_0. This value is related to the rated breaking current of the corresponding voltage level circuit breaker and the related circuit and equipment reliability parameters. For some old lines, transformers and other equipment are obsolete, and the upper limit of the current limit level I_0 is lower. For a new substation, equipment such as transformers and transmission lines is new, and the upper limit of the current limit level I_0 is relatively higher. At this time, in order to effectively limit the short-circuit current to within the safe range, the amount of change in the short-circuit current after the current limiter is installed must be higher than the minimum value of the current that the bus bar needs to reduce. That is:

$$\Delta I_i = I_i - I_0 \le \frac{U_k}{Z_{kk}} - \frac{U_k}{Z_{kk} + \Delta Z_{kk}}\,. \tag{6}$$

From (6) we could get the minimum value of impedance of the installed current limiter:

$$Z_{FCL} \ge \frac{-Z_{ij}^2 \times \Delta U_k}{C_1 I_0 + \Delta U_k (Z_{ij} - C_2)}\,. \tag{7}$$

And the ΔU_k explanation is as follows:

$$\Delta U_k = U_k - U_0 = Z_{kk} I_k - Z_{kk} I_0\,. \tag{8}$$

3. Analysis of short circuit reliability of power network

3.1. Foundation of grid reliability analysis

When a short-circuit fault occurs in the system after UHV access, the current increases sharply, and the operating state of the power grid changes accordingly. The reliability of the equipment decreases and the probability of failure increases. Therefore, the short-circuit current is one of the important factors affecting the reliability of the equipment. The dynamic reliability of the equipment changes with the change of the short-circuit current. How to carry out effective reliability assessment, establish the relationship between grid reliability assessment and fault rate under the grid fault short-circuit current, as well as realize accurate and effective dynamic assessment of grid reliability under short-circuit conditions is the basis of this paper.

The reliability assessment includes static assessment and dynamic assessment, the static assessment is mainly based on operational statistics, and the dynamic assessment is related to grid operation status. The reliability evaluation under the short-circuit condition is based on the historical operation statistics of the equipment, considering the current level when accidents occur, and comprehensively obtaining the reliability level of the actual operation. The operating reliability of the grid under short-circuit conditions is mainly affected by the system fault current, the grid operating state and the external environment. Therefore, the main basis for the reliability assessment of the power grid is also the analysis of these factors. In this paper, a short-circuit factor is mainly considered, and the reliability evaluation model that meets the actual operation is established.

3.2. Reliability comprehensive evaluation model

The reliability analysis of the short-circuit in the grid is a dynamic evaluation process. When the short-circuit fault occurs in the system, the reliability of the grid changes. In this dynamic process, the higher short-circuit current is, the better the relative reliability of the grid is. The lower the value, the greater negative correlation is. Therefore, the electrical quantity such as the short-circuit current level, the probability of failure and the corresponding load loss are quantitatively fitted, and the calculation formula of the reliability evaluation is obtained. Combined with the various parameters collected, the dynamic reliability quantification results can be obtained by (9).

$$f(k) = P(I_k)L(\Delta S_k) + C(x_k). \tag{9}$$

In Equation (9), $P(I_k)$ is the functional relationship between fault probabilities and the short circuit current. The higher the short circuit current is, the higher the fault probability is. $L(\Delta S_k) = \varphi(\Delta S_k)$ is the change rate of load loss under the failure condition. ΔS_k is the loss of load capacity. $C(x_k)$ is constant, which is the quantitative value of reliability evaluation before UHV access, and k is the number of different nodes.

The formula for calculating load capacity is as follows:

$$\begin{cases} Q_k = P_k \times \tan\varphi = K_{\sum Q} \sum\limits_{j=1}^{n} Q_{e,j} \\ S_k = S_0 + \sqrt{P_k^2 + Q_k^2} \\ P_k = K_{\sum P} \sum\limits_{j=1}^{n} P_{e,j} \end{cases} . \tag{10}$$

In this paper, the fault rate and short-circuit current are quantitatively fitted and simulated with a similar S-shaped curve. The S-shaped function is as follows:

$$P(I_k) = \frac{1}{1 + e^{-a(I_k - \mu)}} . \tag{11}$$

In the formula, a and μ are shape parameters, the size of the specific values is related to the lines and equipment. The normal working conditions of the lines and transformers show different reliability quantification values. Therefore, a and μ are changed. That is to say, the values are different under different circumstances. The relationship curve between the fault rate and short circuit current is shown in Fig. 4.

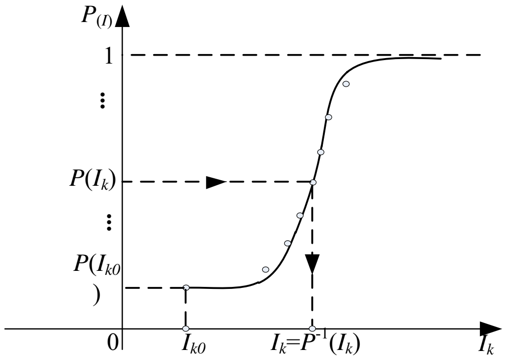


Fig. 4. Relation diagram of fault probability and short circuit current

I_{k0} is the initial value of short circuit current and $P\ (I_{k0})$ is the initial value of fault probability. With the increase of current in the system, the damage to the stable operation of the equipment will also rise, and the probability of failure in the power grid will be higher. When a certain value is reached, the possibility of failure becomes an inevitable result. The reliability evaluation formula obtained by quantification allows one to see that the higher the quantified reliability value, the worse the corresponding reliability, which is negatively correlated with the previous analysis when the failure rate is high and the load loss rate is high too.

4. Current limiter optimization model based on grid reliability

4.1. Optimize the distribution based on the reliability of the flow restrictor grid

Combined with mathematical expressions for quantitative assessment of grid dynamic reliability, the primary task of grid optimization is to conduct reliability assessment. Comprehensively analyze the evaluation results and find the less reliable quantity in the quantitative results as a candidate for current limiter installation. In the case where the current limit is small and the number of candidate points is small, the installation of the fault current limiter is relatively simple, and the enumeration method can be directly used for the test. However, with the increase of a short-circuit limit site in a large power grid, the installation of the fault current limiter is relatively complicated, and the enumeration method is no longer applicable. Therefore, how to effectively narrow down the optimized search range and reduce the calculation time, and meet the security and stability of the grid is to fully consider the dynamic reliability of the grid. In this paper, based on the dynamic reliability evaluation of a power grid, some candidate points are selected among the possible installation sites of many current limiters, and then the optimization algorithm is used to optimize the configuration of the current limiter. The specific steps are as follows.

Step 1: Using PSASP software, calculate the three-phase short-circuit current of all nodes in the whole system, find out short-circuit current exceeding the standard node, and record the three-phase short-circuit current value.

Step 2: Quantify short-circuit current limit data, the initial reliability quantization parameter, and the load loss rate under the fault, and substitute the grid dynamic reliability evaluation formula to evaluate the dynamic reliability of the grid short circuit.

Step 3: Integrate the quantized results to find the candidate location of the current limiter installation location, and proceed to the next optimization scheme.

Step 4: Take the candidate branch as the next optimization branch, determine the number of the restrictor installation and the corresponding installation position, and achieve global optimization configuration.

4.2. Current limiter optimization configuration mathematical model

From the perspective of grid planning and operational economy, the goal of the optimization algorithm is to reduce the number of current limiters installed as much as possible while effectively limiting short-circuit current. Based on the dynamic reliability assessment of the power grid, narrow the search range and select the candidate branch of the current limiter. Then verify the optimization scheme with practical examples.

The current limiting effect evaluation function is:

$$f_1 = \frac{1}{N}\sum_{k=1}^{N} \alpha_k \lambda_k . \tag{12}$$

In the formula, α_k represents the super-punctuation weights, whose magnitude of value is related to the short-circuit current of the station before the current limiter is installed [13]. Before the current limiter is installed, the short-circuit current value is higher, and short-circuit current weight is larger. Under a certain margin, I_0 sets the short-circuit current value. Because the actual reliability level of different lines is different, the setting of the short-circuit current will be different. For example, the reference current in the new line is set to 90% of the rated breaking current, while for some long lines, only 70% of the rated value can be taken as a reference. Therefore, the value of I_0 will change [14, 15].

In order to avoid the effect of limiting the current limit, but the value of each busbar short-circuit current after the current limit is large, it is necessary to calculate the balance of the short-circuit current after the current limiter is installed. Evaluate the overall effect balance of the current limit and optimize the optimal installation plan. Therefore, an evaluation function of the overall horizontal balance after the current limit is established.

The current-limit overall effect balance evaluation function is:

$$f_2 = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(\alpha_k \lambda_k - \frac{1}{N}\sum_{k=1}^{N} \alpha_k \lambda_k\right)^2} . \tag{13}$$

Limiting the short-circuit current scheme, which uses the current limiter, needs to meet three constraints. Firstly, the busbar short-circuit current is smaller than the current-limiting target. Secondly, the current-limiter impedance needs to be higher than the impedance minimum when short-circuit current is effectively limited. And thirdly, the number of installed flow restrictors meets the requirements.

1. Short-circuit current constraint conditions:

$$I_i \leq I_0 \,.$$

2. Current limiting impedance constraints:

$$Z_{\min} \leq Z_{FCL}(x) \leq Z_{\max} \,.$$

3. Restrictor conditions for the number of installed flow restrictors:

$$N_{FCL} \leq M_{\max} \,.$$

$Z_{\max}$ and $Z_{\min}$ are the maximum and minimum values of the current limiter of the current limiter. $N_{\max}$ is the maximum number of installations of the current limiter.

4.3. Current limiter optimization configuration algorithm flow

Consider the overall limit level of the current limiting effect while considering the current limiting effect within the specified margin. In order to simplify the optimization model, the current limiter of the current limiter is 10 ohms, and the number is set to 1–3. Its multi-objective optimization function is:

$$F = \begin{cases} \max(f_1) \\ \min(f_2) \\ I_i \leq I_0 \end{cases} . \tag{14}$$

In the optimized configuration of the current limiter, the current limit level and overall effect are considered comprehensively. Combining the correlation between the two, the construction fitness function is:

$$\min(F) = -c_1 f_1 + c_2 f_2 \,, \tag{15}$$

where: c_1 and c_2 are the weights, and the c_i can be selected according to actual conditions. In this paper, the particle swarm optimization algorithm with wide application and strong sensitivity is used to optimize the configuration [16], and then combined with professional software to verify the reliability of the optimization scheme. The specific process is shown in Fig. 5.

Combined with the analysis in Fig. 5, in the optimized layout, the number of the installed current limiters is set, and the optimization results are calculated and verified, and substituted into the reliability quantization formula for verification. If there is a situation that does not meet the short-circuit current margin, adjust the number of current limiters and re-optimize the calculation until the current limiting effect and reliability conditions are met.

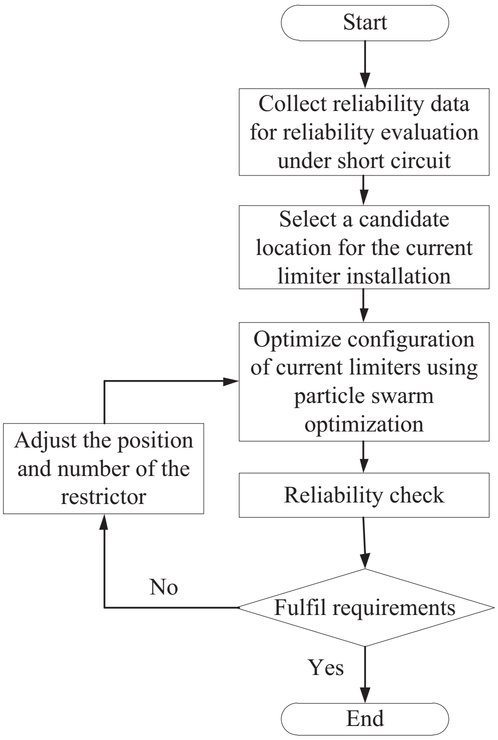


Fig. 5. Optimize algorithm flow chart

5. Case study

5.1. Dynamic reliability assessment of the actual power grid

Taking the UHV grid in a province's plan as an example, in 2020, the province plans are to access the UHV project. In the planning data, due to the UHV access, the short-circuit current increases sharply, even beyond the circuit breaker. The dynamic reliability of the power grid is deteriorated, and the system cannot operate normally and stably. Table 2 shows the short-circuit current changes of the provincial power grid before and after UHV access. Assuming that the rated breaking current of all 500 kV voltage class breakers is 63 kA, three-phase short-circuit current calculations are performed for the planned grid. Table 2 shows the stations with the short-circuit current margin less than 10% in a certain operation mode after UHV access in the province.

Through the investigation and acquisition of data, combined with the short-circuit current calculation results, the dynamic reliability assessment of the provincial power grid was performed. Fig. 6 shows the results of the partial reliability evaluation.

Combined with the analysis in Fig. 6, the relatively weak sites in the province's power grid are: MS, NC, YX, LF, JX, etc., and the geographical location is relatively scattered. Due to the lack of site electrical parameters in the post-planning, reliability analysis is not performed for this, but it can be combined with the short-circuit current limit condition to determine whether

Table 2. Relation diagram of fault probability and short circuit current

Factory, station 500 kV bus	**Three-phase short-circuit current (kA)**		**Margin**
	Before UHV connection	**After UHV connection**	
CT	–	59.226	6.3%
JX	31.52	60.359	4.2%
MS	46.145	59.909	4.9%
NC	38.961	62.334	1.1%
XM	45.94	59.532	5.5%
YX	45.89	62.026	1.5%

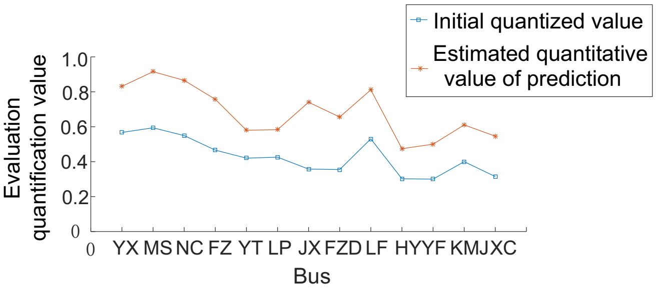


Fig. 6. Reliability assessment results of grid short circuits

it is a candidate installation site for the current limiter, and then analyze the possible installation position of the current limiter.

5.2. Reliability assessment of the actual power grid

Based on the short-circuit dynamic reliability evaluation of the power grid, the current limiter is properly installed to effectively limit the short-circuit current. Economically, because the current limiter is expensive and the current limiter with variable current-resistance value is more expensive, the current limiter value of the current limiter is fixed at 10 Ω [17], and the number and position of the current limiter are changed. There are 31 500 kV stations in the planned provincial power grid, and there are 179 candidate branches. Combined with the operating conditions of the fault current limiter and the evaluation of the dynamic reliability of the power grid, the award current limiter is installed with low reliability. On the branch road, the system was reduced from the original 179 branches to 38 branches, greatly reducing the scope of the search. It is necessary to re-number the branches, set the number of installations from 1 to 3, and the weight coefficients to 2/3 and 1/3. Since the actual reliability parameter data is not easy to collect, for the convenience of calculation, the short-circuit current upper limit is 90% of the rated breaking capacity of the unified circuit breaker. The adaptive function values of the province's planned grid corresponding to different installation ceilings and optimal configuration points are shown in Table 3.

Table 3. Adaptive function values of optimal configuration

Number of current limiters	**one**	**two**	**three**
Optimal function value	0.004009	0.010294	0.012723

Table 4 shows the pre-selection scheme for the optimal layout of the current limiter of the provincial power grid in 2020 (repeated branch is counted as one).

Table 4. Optimize the pre-selection scheme for configuring the current limiter

Limiter installation number	**Pre-installed line**
1	YX-NC
2	YX-MS, NC-JX
3	YX-MS, CT-JX, FZ-CR

The more the number of installations, the higher the economy, but because the cost of the ultra-high pressure current limiter is higher, the number of installations is not more than three, so the solution effect can be verified according to the above-mentioned current limiting scheme.

5.3. Analysis of current limiting effect

Combined with the analysis of section 4.2 and the pre-selection scheme of the current limiter installation, after the current limiter is installed, the short-circuit current is calculated and verified. When the number of the current limiter is one, the installation line is YX-NC. Table 5 shows the short-circuit current calculation result, the current limiter is installed at the partial margin (the rated short-circuit capacity of the circuit breaker is referenced to 63 kA).

Table 5. The current limiter is installed on YX-NC line to limit the flow effect

Bus name	**Short circuit current (kA)**	**Margin**
CT	54.519	13.5%
CXN	51.441	18.3%
JX	52.918	16%
MS	55.477	12.0%
NC	48.444	23.1%
NCD	45.417	27.9%
XM	55.154	12.5%
YX	46.736	25.8%

It can be seen from the above table that the installation of a current limiter has a significant effect on short-circuit current limiting of the installation line site, and at the same time, the short-circuit current margin of other stations has increased. The scheme satisfies the short-circuit current margin of all stations above 10%, and the short-circuit current distribution is uniform. However, the short-circuit current of each station is not low overall, and short-circuit current margin of many stations is between 10% and 15%. Combined with the reliability evaluation results of grid lines and transformer equipment, the short-circuit current margin of some substation bus stations needs to reach 20% to 30%, such as NC, MS, YX and other plant stations. Therefore, from the perspective of dynamic reliability analysis of the power grid, installing one current limiter does not effectively limit the short-circuit current within the safe range, and the safe and stable operation of the power grid is still threatened.

Therefore, the installation scheme of the current limiter can be set to two, and the optimal configuration of the current limiter can be re-configured. Calculate the short circuit current. The analysis of short-circuit current levels in accordance with the installation scheme of Table 4 is shown in Table 6.

Table 6. Install 2 (YX-MS, NC-JX) current limiter

Bus name	**Short circuit current (kA)**	**Margin**
CT	48.023	25.0%
CXN	46.548	26.1%
JX	42.754	32.1%
MS	44.076	30.0%
NC	39.732	36.9%
NCD	40.904	35.1%
XM	43.886	30.3%
YX	39.549	37.2%

Combined with Table 6, from the overall effect analysis, when two current limiters are installed, the short-circuit current of each station is greatly reduced, and the short-circuit margin is greatly increased, which is above 25%, the problem of insufficient quantity has been effectively limited. At the same time, combined with the dynamic reliability assessment analysis after the short-circuit of the power grid, the bus margin of each station basically meets the requirements of safe and stable operation after quantitative evaluation of its lines and equipment.

In order to effectively test the optimal number of installed flow restrictors, the following is an analysis of the effect of setting the number of current limiters to three. Combined with Table 4, the calculation results of the short-circuit current for the portion with an insufficient margin are shown in Table 7.

Combined with the analysis in Table 7, when installing three current limiters, the short-circuit current margin of the site with an insufficient margin is greatly improved, which is basically above 30%, but the short-circuit current margin is also improved for stations with far-distance installation lines. Stay within the normal range.

Table 7. Install 3 (YX-MS, CT-JX, FZ-CR) current limiter

Bus name	**Short circuit current (kA)**	**Margin**
CT	41.154	34.7%
CXN	46.344	26.4%
JX	32.953	47.7%
MS	43.922	30.3%
NC	35.879	43.1%
NCD	34.406	45.4%
XM	43.733	30.6%
YX	28.41	54.9%

In order to verify whether the grid can be reliably and stably operated under short-circuit faults after the installation of the current limiter, the dynamic reliability of the grid after the current limiter is installed is quantitatively evaluated. The result is shown in Fig. 7.

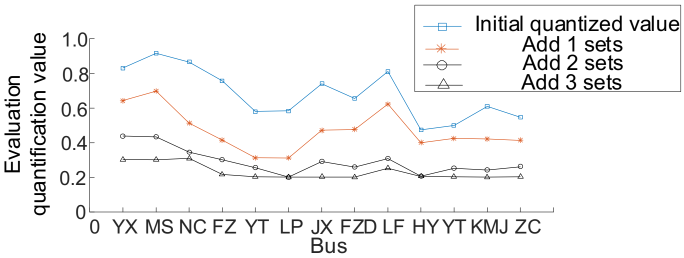


Fig. 7. Evaluation results of short-circuit reliability before and after adding current limiter

Combined with the analysis of Fig. 7, from the current limiting effect and the dynamic reliability analysis after the short circuit after installation, installing one current limiter can keep the short-circuit current margin at 10% or above, but the reliability is still not high. For the case of installing two current limiters, the current limiting effect is relatively good, even if the distance from the current limiter installation position is far, the short circuit current margin is more than 15%. The installation of three current limiters can also effectively limit the short circuit current. Therefore, it is recommended to install two current limiters to limit the short-circuit current, which can effectively limit the short-circuit current based on dynamic reliability, while taking into account the economics of the power grid.

6. Conclusions

This paper investigates the background problem of the short-circuit current exceeding the standard after it occurs in the UHV power grid. An optimization scheme based on grid dynamic reliability assessment is proposed for the installation of optimization configuration of the current limiter, and it is verified by the actual grid of a chosen province. We mainly obtained the following conclusions:

1. Based on the dynamic reliability assessment of the grid under short-circuit condition, the possible fault level of the grid and the level of a short-circuit limit are fully considered, and the location with low reliability is selected as the candidate for the current limiter installation, thereby narrowing the optimized layout.
2. This paper proposes a reliability-based current limiter with the use of the large power grid optimization configuration method, combined with line and equipment reliability issues, and according to the reliability of different equipment the paper sets the flow restrictor layout. The effect of maximizing the short-circuit current can be realized on the basis of the minimum current limiter, and at the same time, the reliability level of the grid operation can be effectively improved under the premise of the economy.
3. Based on the dynamic reliability of the power grid, this paper optimizes the layout of the current limiter. However, the reliability assessment only uses the failure rate and short-circuits current variation as the evaluation criteria. The impact of the relay protection after current limiting is not considered. This is a problem that needs further study.

Acknowledgements

Project Supported by Department of education of Jiangxi Province (Grant No. GJJ160528).

References

[1] Ying Z., Liu T., Wang J., *Global optimization algorithm for fault current limiter configuration based on rearranged particle swarm optimization*, Electric Power Automation Equipment, vol. 38, no. 02, pp. 145–152 (2018).

[2] Ying Z., Liu T., Wang J. *et al.*, *Adjustment for Power Grid Configuration to Limit Short-circuit Current Based on Improved Ant Colony Optimization*, Automation of Electric Power Systems, vol. 42, no. 01, pp. 144–150 (2018).

[3] Huang G., Luo D., Li S. *et al.*, *Optimal line-outage measure based on comprehensive sensitivity analysis to limit short-circuit current*, Power System Technology, vol. 40, no. 01, pp. 309–315 (2016).

[4] Du T., Zhang X., Zhang X. *et al.*, *Optimize the Allocation of Global Fault Current Limiter Based on Genetic Algorithms*, Electronics Quality, no. 09, pp. 1–5+9 (2016).

[5] Xu K., Sun T., Han S. *et al.*, *Optimal sitting and parameter selection for fault current limiter constrained with power losses*, Power System Protection and Control, vol. 43, no. 05, pp. 21–26 (2015).

[6] Hu W., Wei Z., Sun G. *et al.*, *Optimal allocation of superconducting fault current limiters based on sensitivity method*, Automation of Electric Power Systems, vol. 36, no. 22, pp. 62–67 (2016).

[7] Xiao H., Li Q., Zhang Y. *et al.*, *Optimization of Fault Current Limiter Configuration Based on Improved NSGA-2*, Power System Technology (2016).

[8] Chen B., Wei L., Lei Y. *et al.*, *Immune algorithm based pareto multi-objective optimal allocation of high temperature superconductor-fault current limiters*, Power System Technology (2015).

[9] Mao J., Jiang P., Hu W., *Research on Optimal Location of CLI Using PSO Algorithm and its Application*, Jiangsu Electrical Engineering, vol. 29, no. 05, pp. 21–25 (2010).

[10] Li J., Teng H., Guo N., *An Optimal Decision to Restrain Short Circuit Current for 500 kV Power Grids with Combinatorial Weighting Method of Relative Entropy*, Power System Technology, vol. 40, no. 06, pp. 1811–1817 (2016).

[11] Lou X., Wang W., Wang B. *et al.*, *A grid operation mode optimization method for controlling short-circuits current level based on WARD equivalence*, Power System Protection and Control, vol. 45, no. 18, pp. 128–136 (2017).

[12] Liao G., Xie X., Hou Y. *et al.*, *Analysis on the Problems of Three-phase Short-circuit Current Over-limited of 500 kV Bus When UHV Connected to Hunan Power Grid*, High Voltage Engineering, vol. 41, no. 03, pp. 747–753 (2015).

[13] Teng J.H., Lu C.N., *Optimum fault current limiter placement with search space reduction technique*, Iet Generation Transmission and Distribution, vol. 4, no. 04, pp. 485–494 (2015).

[14] Hongbo Q., Yanqi W., Cunxiang Y. *et al.*, *Research on the operational performance of high speed permanent magnet generator with controlled rectifier in distributed generation*, Archives of Electrical Engineering, vol. 67, no. 4, pp. 899–913 (2018).

[15] Asghar A., Arani K., Bayati N. *et al.*, *Fault Current Limiter optimal sizing considering different Micro-grid operational modes using Bat and Cuckoo Search Algorithm*, Archives of Electrical Engineering, vol. 67, vol. 2, pp. 321–332 (2018).

[16] Mehdinejad M., Mohammadi-Ivatloo B., Dadashzadeh-Bonab R. *et al.*, *Solution of optimal reactive power dispatch of power systems using hybrid particle swarm optimization and imperialist competitive algorithms*, International Journal of Electrical Power and Energy Systems, vol. 83, no. 0142–0615, pp. 104–116 (2016).

[17] Ying Z., Wang J., Chen X. *et al.*, *An Optimal Configuration Scheme for Ultra-high Voltage Short-circuit Current Limiter in Guangdong Power Grid*, Automation of Electric Power Systems (2012), DOI: 10.3969/j.issn.1000-1026.2012.04.018.