Optimal Configuration of Fault Current Limiter Based on Multi-objective Decision

Wenxiong Mo\textsuperscript{1a}, Yong Wang\textsuperscript{1b}, Jun Chen\textsuperscript{1c}, Shengya Qiao\textsuperscript{1d}, Lu Zhu\textsuperscript{1e} and Rong Fu\textsuperscript{2f}

\textsuperscript{1} Guangzhou Power Supply Bureau Co., Ltd, Guangzhou 510620, Guangdong Province, China
\textsuperscript{2} School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, Hubei Province, China

\textsuperscript{a}gzmwx@139.com; \textsuperscript{b}wangy@guangzhou.csg.cn; \textsuperscript{c}laochen.locky@163.com; \textsuperscript{d}396349222@qq.com; \textsuperscript{e}315995738@qq.com; \textsuperscript{f}furong96@outlook.com

Abstract. To perfect the application of the fault current limiter in grid and improve the use efficiency, an optimal configuration method of fault current limiter based on multi-objective decision is proposed. Firstly, use rate of current change to select alternative branches, then taking the cost and current-limiting effect of fault current limiter as the targets, considering installation location, quantity of fault current limiter comprehensively, using \( \alpha \)-method to determine the weight coefficient, establish multi-objective optimization model, and use immune algorithm to obtain the optimal scheme of branch installation. Next, by comparing the configuration of fault current limiter in the bus connection, the best configuration scheme is obtained. Finally, this method is verified by analyzing the IEEE39 node standard network.

1. Introduction

As the load level continues to rise, the scale of power system continues to increase, the short-circuit current has become one of the main factors that endanger the stability, safety and reliability of power systems [1-2]. Therefore, Fault Current Limiter, which can limit the short-circuit current without affecting the normal operation of the power system, has important research significance.

The key to optimize the fault current limiter is to configure the number, impedance and installation position of the FCL with the goals of reliability and economy [1].

The references\cite{2-5} optimizes the type, the use scale, the installation range and the impedance value of the fault current limiter; In reference \cite{6}, a multi-objective optimization model is established based on system power flow constraints, and the incomplete enumeration method and discrete particle swarm optimization algorithm are used to optimize the configuration of short-circuit current limiting for large-scale and complex networks; In reference \cite{7}, based on the immune algorithm, Pareto multi-objective optimization is used to study the configuration of high temperature superconducting fault current limiters; In reference \cite{8}, the fast-non-dominated sorting genetic algorithm is used to obtain a multi-objective optimization model based on multi-objective decision and Pareto optimal solution. All of the studies above have been optimized the installation of the fault current limiter in the branch, but the bus connection has not been further considered.

Based on the above research, this paper proposes an optimal configuration method of fault current limiter based on multi-objective decision. The short-circuit current rate-of-change sensitivity analysis is
used for branch screening. The installation position, installation quantity and current limiting effect of the fault current limiter are comprehensively considered. The fault current limiter impedance value and short-circuit current of node are constrained. With the goal of cost and current limiting effect, the weighting coefficient is determined by the $\alpha$-method, and the multi-objective optimization model is established. Then, the optimization result of the branch installation is obtained by using the immune algorithm, and the classification enumeration method is used to optimize the configuration of the fault current limiter in the bus connection. Finally, analyze and compare both schemes to get the best one.

2. Mathematical model and installation location selection of FCL

2.1. Mathematical model of FCL

The High Coupled Split Reactor-Fault Current Limiter (HCSR-FCL) used in the paper working principle is shown in figure 1.

![Figure 1. The principle diagram of HCSR-FCL](image)

The HCSR-FCL consists of two coils that are coupled to each other. The two coils are short-circuited at one end, two quick switches on the same side is designed to eliminate the potential difference between the two splitting coils. When the two branches current is balanced, the magnetic flux generated by the two coils cancel each other out in the common magnetic circuit, and only shows a small leakage inductance; when the two branches are not balanced or only a single branch is on, the magnetic flux generated by the coil is large, which can limit the fault current.

According to the principle of short-circuit calculation, when the three-phase short-circuit fault occurs at node $k$, its short-circuit current is:

$$I'_k = \frac{1}{Z_{kk} + z_f}$$  \hspace{1cm} (1)

Where $Z_{kk}$ is the self-impedance of node $k$; $z_f$ is the transition impedance of node $k$; $I'_k$ is the short-circuit current of node $k$.

When HCSR-FCL is put into operation, use additional branch method to modify the node impedance matrix. As shown in figure 2, series impedance $Z_{FCL}$ can be equivalent to impedance $Z_f$ in parallel, which can be calculated by equation (2).

$$Z_f = \frac{(Z_{pp} + Z_{FCL})}{Z_{pq} + Z_{FCL}}$$  \hspace{1cm} (2)

Then, after the short-circuit fault occurs, when the single-arm impedance of HCSR-FCL is $Z_{FCL}$, the self-impedance of any node $k$ is expressed as:

$$Z_{ik} = Z_{ik} - \frac{(Z_{kp} - Z_{kq})^2}{Z_{pp} + Z_{qq} - 2Z_{pq} + Z_f} = Z_{ik} + \Delta Z_{ik}$$  \hspace{1cm} (3)
Figure 2. The equivalent impedance of HCSR-FCL

Where $Z_{ik}$ is the self-impedance of node k before HCSR-FCL put into operation, $\Delta Z_{ik}$ is the change of node k's self-impedance after HCSR-FCL putting into operation.

2.2. Screening based on sensitivity analysis

In the large transmission and distribution network, in order to reduce the amount of calculation and avoid falling into the “dimensional disaster”, a sensitivity analysis method can be used to screen out a certain range in advance.

References [4, 7] proposed two methods of sensitivity analysis, namely the sensitivity of the node impedance increment based on the branch impedance increment and the sensitivity of short-circuit current rate-of-change. In the actual comparative study, the sensitivity of short-circuit current rate-of-change has shorter computation time and more operability when calculating the current limiting effect on multiple nodes. Therefore, in this paper, this method is used to screen the branch.

When the three-phase short-circuit fault occurs in the grid, the short current of node $k$ is $I_k$, and the short-circuit current rate-of-change node $k$ after the FCL is put into the branch $p-q$ is

$$C_{pq}^k = \frac{\Delta I_k}{I_k} = \left( \frac{U_k^{(0)}}{Z_{ik} + \Delta Z_{ik}} - \frac{U_k^{(0)}}{Z_{ik}} \right) \left( \frac{U_k^{(0)}}{Z_{ik}} \right)$$

$$= - \frac{\Delta Z_{ik}}{Z_{ik} + \Delta Z_{ik}}$$

(4)

In equation (4), $C_{pq}^k$ is the short current rate-of-change after the fault current limiter is installed on the branch $p-q$, $\Delta I_k$ is the short current change amount of the node $k$, $Z_{ik}$ is the self-impedance of the node $k$ before the FCL is installed; $\Delta Z_{ik}$ is the self-impedance change amount of the node $k$ after the FCL is installed.

The equation (4) can be used to calculate the short current rate-of-change of each branch to the node. According to the value, the first few branches can be selected as the candidate branch, and the optimal configuration of FCL can be performed on this basis.

3. Optimization configuration of FCL

3.1. Objective function and constraint conditions

From the overall effect of the network, the cost calculation of HCSR-FCL is mainly affected by the installed quantity and the total impedance of the FCL. Therefore, the cost function of the HCSR-FCL is as follows:

$$f = 2 \sum_{i=1}^{N} Z_{FCL} + \omega N_{FCL} + F_a$$

(5)
In equation (5), $Z_{FCL}$ is the impedance value of a coil in the HCSR-FCL, one HCSR-FCL contains two identical coils; $\omega$ is the installation cost coefficient of the HCSR-FCL; $N_{FCL}$ is the total number of installations of the HCSR-FCL on the branch; $F_p$ is the penalty function setting to ensure the short current of each node can be limited to the allowed value after the HCSR-FCL is put into operation.

In order to facilitate the calculation of the objective function, a current-limiting cost sub-function is proposed:

$$F_1 = \frac{1}{f} = \frac{1}{2\sum_{i=1}^{N_{FCL}} Z_{FCL}(i) + \omega N_{FCL} + F_p}$$

(6)

The current limiting effect of each node can be determined according to the ratio of the difference between the short-circuit current value and the target current value. In equations below, $\eta_k$ is the current limiting effect on the node $k$ after the fault current limiter is put into operation; $I_G$ is the target current; $I_k$ is the short current of the node $k$ after the fault current limiter is put into operation; $Z_{Gk}$ is the self-impedance of the node $k$ under the target current; $U_k^{(0)} = 1$ when calculating in standard value.

$$\eta_k = \frac{I_G - I_k}{I_G} = \frac{\left(U_k^{(0)} - U_k^{(0)}\right)}{Z_{Gk}} = \frac{U_k^{(0)}}{Z_{Gk}}$$

(7)

$$I_k = \frac{U_k^{(0)}}{Z_{ik}}$$

(8)

$$Z_{Gk} = \frac{U_k^{(0)}}{I_G}$$

(9)

When there is only one excessive node in the system, equation (7) is the current-limit effect sub-function; when there are multiple excessive nodes, the current-limit effect sub-function of the FCL is

$$F_s = \sum_{i=1}^{r} \epsilon_i \eta_k$$

(10)

Where, $\Gamma$ is a set of all nodes in the system that do not meet the requirements; $\epsilon_i$ is a weight coefficient, which is used to balance the current limiting effect between excessive node and insufficient margin node. When the original short-circuit current of the node $k$ is greater than $I_G$, the node $k$ is an excessive node, and $\epsilon_k = 1$; when the original short current of the node $k$ is smaller than $I_G$ but greater than margin of short-circuit current $I_M$, the node $k$ is an insufficient margin node, and $\epsilon_k = I_k/I_G$.

In the multi-objective mathematical model, in addition to the objective functions and decision variables, the optimization of the fault current limiter configuration must satisfy several constraints:

1) Fault current limiter impedance value constraint

The impedance value that HCSR-FCL can be put into the line when a short circuit fault occurs must meet:

$$0 \leq Z_{FCL}(i) \leq Z_{max}$$

(11)

In equation (11), $Z_{FCL}(i)$ is the fault current limiter impedance value that can be input on each candidate branch; $Z_{max}$ is the maximum impedance value of the fault current limiter that is allowed to be input on each branch and to prevented the cost from being excessive.

2) Short-circuit current constraints of nodes in the power grid

The purpose of installing the FCL is to limit the short-circuit current of the node of the power grid to a suitable range. The constraints are as follows:
\[ I_k < I_G \]  \hspace{1cm} (12)

In addition, there should be no isolated nodes in the power grid, and the active power and reactive power in the power flow calculation must be balanced.

Therefore, the mathematical model of FCL configuration optimization based on multi-objective decision is as follows:

\[
F = \begin{cases} 
\max(F_1), \\
\max(F_2), \\
0 \leq Z_{\text{FCL}}(i) \leq Z_{\text{max}} \\
I_k < I_G
\end{cases} \quad (13)
\]

3.2. \( \alpha \)-method to determine the weight coefficient of the multi-objective optimization mathematical model

According to reference [9], the weight coefficient can directly reflect the degree of importance of the objective function. It can be known from the definition of the fault current limiter cost sub-function and the current limiting effect sub-function that the larger the value of the current limiting cost sub-function, the smaller the value of the current limiting effect sub-function. Obviously, there is no absolute optimal solution for the multi-objective optimization mathematical model. Therefore, this paper chooses to use the \( \alpha \)-method to determine the weight coefficient of the multi-objective optimization mathematical model.

Firstly, introduce an overall objective function \( F \):

\[
F = \lambda_1 f_1 + \lambda_2 f_2 \quad (14)
\]

In equation (14), \( F \) is the function value for determining the energy saving potential of the line; \( \lambda_1, \lambda_2 \) is the weight coefficient, \( \lambda_1 + \lambda_2 = 1, \lambda_1 > 0, \lambda_2 > 0 \); \( f_1 \) is the cost sub-function value of the FCL, and \( f_2 \) is the current limiting effect sub-function value of the FCL.

Set the optimal solution for the single-objective problem \( \left( P_{ij} \right) \max f_i(x) \) \( (i=1,2; x \in R) \) as \( x' \) \( (i=1,2) \), remark:

\[
\begin{align*}
&f_1(x') = f_1^1 \\
&f_2(x') = f_2^1 \\
&f_1(x'') = f_1^2 \\
&f_2(x'') = f_2^2
\end{align*} \quad (15)
\]

As shown in figure 3, in the image space, make a straight line over the point \((f_1^1, f_2^1)\) and \((f_1^2, f_2^2)\).

\textbf{Figure 3.} The Schematic diagram of the method for determining the weight coefficient

Let the linear equation be

\[ \lambda_1 f_1 + \lambda_2 f_2 = \alpha \quad (16) \]

Then there is
The premise of the $\alpha$-method is that there is no absolute optimal solution, that is, the optimal optimization result cannot be directly obtained by comparing the two sub-objective functions. Therefore, there must be

$$\begin{cases}
\lambda_1 + \lambda_2 = 1 \\
\lambda_1 f_1^1 + \lambda_2 f_1^2 = \alpha \\
\lambda_1 f_2^1 + \lambda_2 f_2^2 = \alpha
\end{cases}$$

(17)

Solving equation (17) under the condition of equation (18), we can get equation (19) for solving two weight coefficients:

$$\begin{cases}
f_1^2 > f_1^1 \\
f_2^1 > f_2^2
\end{cases}$$

(18)

$$\begin{aligned}
\lambda_1 &= (f_1^2 - f_1^1) / [(f_1^2 - f_1^1) + (f_2^2 - f_2^1)] \\
\lambda_2 &= (f_2^1 - f_1^1) / [(f_1^2 - f_1^1) + (f_2^1 - f_2^2)] \\
\lambda_1 > 0, \lambda_2 > 0, \lambda_1 + \lambda_2 &= 1
\end{aligned}$$

(19)

3.3. Optimization steps based on immune algorithm

![Flowchart](image_url)

Figure 4. FCL optimization configuration flow chart based on AIA
In this paper, the immune algorithm is used to optimize the multi-objective configuration of the FCL. The scheme realizes the comprehensive optimization of the two sub-objective functions.

The specific operation steps of the optimization process based on the immune algorithm is shown in figure 4.

The gene length of the antibody in the immune algorithm is the number of candidate branches. The gene coding of the antibody indicates the installation number of the FCL, and the position of the gene is the installation position of the FCL. Others are immune algorithms [10-11] normal operation, so it won't be gone into details.

4. Case analysis

4.1. Simulation case

This paper takes IEEE39 nodes system as an example, as shown in figure 5, for FCL optimization configuration. Let the target value of the short-circuit current $I_g=84$pu. The margin of the short-circuit current is 10% of the target value, and the margin value of the short current $I_m=75.6$ pu.

![IEEE39 nodes system](image)

**Figure 5.** IEEE39 nodes system

When the three-phase short circuit fault occurs, the short-circuit current exceeds the standard and the nodes that do not meet the margin requirements are shown in Table 1.

It is apparent from the table that the three-phase short-circuit current of the node 39 is particularly large, because the transient reactance of the generator connected to the node 39 is extremely small, so using the HCSR-FCL to limit its short current is not economical in actual operation, and the effect is not good. It is more suitable to limit the short current of node 39 by means of disconnection [12]. Therefore, this paper only studies the FCL optimization for the Node 2, Node 16, and Node 30.

| Node number | $I_k$/pu | Excessive / Insufficient margin |
|-------------|----------|-------------------------------|
| 2           | 85.2     | excessive                     |
| 16          | 82.4     | insufficient margin           |
| 30          | 79.1     | insufficient margin           |
| 39          | 280.9    | excessive                     |
4.2. Branch screening
According to the HCSR-FCL start condition, the sensitivity of the short-circuit current rate-of-change on each node is obtained when the FCL installed on each branch is operated.

The magnitude of the short-circuit current rate-of-change of the node that does not meet the requirement is sorted, and each node is analysed based on the first 6 bits, as shown in Table 2. Exclude duplicate branches to get the final installation range, as shown in Table 3.

Table 2. Branch screening based on sensitivity of short current change rate

| Node that does not meet the requirements | Branches (rate-of-change)                          |
|-----------------------------------------|--------------------------------------------------|
| 2                                       | 1-2(1.76%);1-39(1.76%);2-3(4.22%);                |
|                                         | 2-25(3.94%);2-30(5.55%);25-37(1.56%);             |
| 16                                      | 14-15(2.12%);15-16(2.12%);16-17(4.44%);           |
|                                         | 16-19(3.52%);16-21(1.71%);19-33(1.97%);           |
| 30                                      | 1-2(0.44%);1-39(0.44%);2-3(1.07%);                |
|                                         | 2-25(1.00%);2-30(6.81%);25-37(0.39%);             |

Table 3. Range based on short-circuit current rate-of-change sensitivity

| Branches name                        |
|--------------------------------------|
| 1-2; 1-39; 2-3; 2-25; 2-30; 14-15;    |
| 15-16; 16-17; 16-19; 16-21; 19-33; 25-37|

4.3. HCSR-FCL configuration optimization on branch
According to the content above, the FCL configuration is optimized based on the immune algorithm. The parameters of the immune algorithm are set as follows: the population size is set to 40, the memory capacity is set to 100, the maximum number of iterations is set to 5000, the gene length of the antibody is set to 12, the penalty function is set to 10000, the crossover probability is set to 0.5, the mutation probability is set to 0.4, and the diversity evaluation parameter is set to 0.95.

For economical and practical considerations, we only install one HCSR-FCL on each branch. Because the impedance of HCSR-FCL is fixed during production, and consider the current limiting range and give the impedance value constraint.

\[
Z_{FCL}(\ell)_{\text{max}} = 0.0084 \text{pu}
\]  

According to reference [8], take \(\omega=5\). Taking the cost sub-function \(F_1\) as the horizontal axis and the current limiting effect sub-function \(F_2\) as the vertical axis, the partial results obtained are shown in figure 6.

Figure 6. HCSR-FCL configuration optimization results in the grid (n = 0,1)
It can be seen from the figure that the cost sub-function $F_1$ of HCSR-FCL and the HCSR-FCL current limiting effect sub-function $F_2$ are inversely proportional to the general trend. In order to obtain the appropriate weight, according to the equation (19)

$$
\lambda_1 = \left( \frac{f_2^1 - f_1^2}{f_1^2 - f_1^1} \right) \left( \frac{f_2^1 - f_1^2}{f_1^2 - f_1^1} \right) = 0.685
$$

$$
\lambda_2 = \left( \frac{f_2^1 - f_1^2}{f_1^2 - f_1^1} \right) \left( \frac{f_2^1 - f_1^2}{f_1^2 - f_1^1} \right) = 0.315
$$

Substituting $\lambda_1$ and $\lambda_2$ into equation (14) to perform optimization calculation of multi-objective model. Finally, the fault current limiter configuration scheme obtained is shown in Table 4. In this case, the cost sub-function $F_1 = 0.1993$, the current limiting effect sub-function $F_2 = 0.1803$. After the FCL is put into operation, the total value of the drop of short-circuit current is 10.54 kA, and the short-circuit current of the node is shown in figure 7.

**Table 4. Optimization configuration of FCL**

| Branch   | Number of FCLs | Branch   | Number of FCLs |
|----------|----------------|----------|----------------|
| 1-2      | 0              | 15-16    | 0              |
| 1-39     | 0              | 16-17    | 0              |
| 2-3      | 0              | 16-19    | 0              |
| 2-25     | 0              | 16-21    | 0              |
| 2-30     | 1              | 19-33    | 0              |
| 14-15    | 0              | 25-37    | 0              |

*Figure 7. Optimization scheme ($Z_{FCL}=0.0084$ pu)*
4.4. HCSR-FCL configuration optimization on bus

![Diagram of HCSR-FCL configuration optimization on bus]

(a) HCSR-FCL on bus 30  (b) HCSR-FCL on bus 2  (c) HCSR-FCL on bus 16

Figure 8. Fault current limiter installed on bus 2, bus 16 and bus 30

It is assumed that the following bus lines have been split, that is, the cost of the splitting bus lines is not considered, and the cost function is only affected by the impedance value of the fault limiter and the number of installations. To contrast with the branch configuration schemes, consider that one fault current limiter is installed on bus 2, bus 16 and bus 30 respectively (in this case, the cost can be considered the same due to the fixed impedance and quantity of the FCL), as shown in figure 8.

Table 5. The connection between the original node/the newly added node and other nodes

| (a)Bus 30 | (b)Bus 2 |
|-----------|----------|
| Scheme no. | 30' | 30 | Scheme no. | 2' | 2 |
| 1          | G    | 2   | 2          | 25,30 | 1,3 |
| 3          | 3,30 | 1,25 |
| 4          | 1,30 | 3,25 |

(c)Bus 16

| Scheme no. | 16' | 16 |
|------------|-----|----|
| 5          | 15,17 | 19,21,24 |
| 6          | 15,19 | 17,21,24 |
| 7          | 15,21 | 17,19,24 |
| 8          | 15,24 | 17,21,24 |
| 9          | 17,19 | 15,21,24 |

| Scheme no. | 16' | 16 |
|------------|-----|----|
| 5          | 17,21 | 15,19,24 |
| 6          | 17,24 | 15,19,21 |
| 7          | 19,21 | 15,17,24 |
| 8          | 19,24 | 15,17,21 |
| 9          | 21,24 | 15,17,19 |

Table 6. Effect of different installation schemes

(a)Install a FCL on Bus 30

| Bus name | 2 | 16 | 30 | 30' |
|----------|---|----|----|-----|
| before   | 85.18376 | 82.43575 | 79.14378 | -- |
| after    | 85.17086 | 82.41231 | 79.14111 | 47.53833 |

(b)Install a FCL on Bus 2

| Bus name | 2 | 2' | 16 | 30 |
|----------|---|----|----|----|
| before   | 85.18376 | -- | 82.43575 | 79.14378 |
| 2        | 71.53226 | 76.58278 | 81.97229 | 77.02138 |
| after    | 71.1357 | 76.93333 | 82.28842 | 77.11471 |
| 4        | 72.92076 | 74.98176 | 81.46842 | 76.00746 |
(c) Install a FCL on Bus 16

| Bus name | 2   | 16   | 16'   | 30   |
|----------|-----|------|-------|------|
| before   | 85.18376 | 82.43576 | --     | 79.14378 |
| 5        | 83.93486 | 72.94782 | 70.6405 | 78.85613 |
| 6        | 84.9626 | 74.39849 | 69.48991 | 79.09353 |
| 7        | 85.08196 | 76.92309 | 67.13695 | 79.12082 |
| 8        | 85.13495 | 78.33022 | 64.89294 | 79.13292 |
| after    | 84.87238 | 71.16274 | 72.91254 | 79.07286 |
| 9        | 84.70694 | 74.14276 | 70.72133 | 79.03488 |
| 10       | 84.54515 | 75.82152 | 68.66815 | 78.99763 |
| 11       | 84.44876 | 75.14124 | 69.06493 | 78.97538 |
| 12       | 84.61905 | 76.74855 | 66.89652 | 79.01466 |
| 13       | 84.79545 | 63.01515 | 78.48036 | 79.05522 |

The preliminary analysis of any of the above two modes on the bus 2 and 16 is carried out. The results show that the bus 2 has a better current limiting effect in mode 2+2, and the bus 16 has a better current limiting effect in mode 2+3. Finally, the classification enumeration method is used. The specific scheme is shown in Table 5. The current limiting effect of installing an FCL on the bus connection is shown in Table 6.

From the table data, the method of installing HCSR-FCL on bus 2 using scheme 4 enables the short-circuit current of all nodes (except node 39, not considered) to be limited to the short-circuit current target value, and the total number of node short-circuit current drops is the most. It is the most economical and effective HCSR-FCL configuration measure among the above schemes. Compared with the optimal branch configuration scheme in Section 4.3, it can be found that both schemes use only one HCSR-FCL for node short-circuit current limitation. However, the scheme of installing the HCSR-FCL on the bus 2 connection has more total short-circuit current drops and better current limiting effect. Therefore, the scheme shown in Figure 8(b)(2) which install the HCSR-FCL on the bus 2 is the optimal configuration scheme in IEEE39 nodes standard system.

5. Conclusion
This paper establishes a mathematical model for HCSR-FCL configuration optimization in the power grid. Considering the HCSR-FCL impedance and the node short-circuit current constraint installed on the branch, the artificial immune algorithm with faster search speed and stronger global search ability than genetic algorithm is used to determine the weight coefficient by α method. The cost sub-function and the current limiting effect sub-function are used to perform multi-objective optimization analysis on the configuration of HCSR-FCL on the grid branch. On this basis, using the classification enumeration method, analyse the different installation position of HCSR-FCL on the bus connection, and the optimal configuration scheme of the HCSR-FCL on the bus is obtained.

The simulation verification of the IEEE39 nodes system shows that the optimal configuration scheme on the branch is more convenient to use. However, for complex networks with many excessive and insufficient margin nodes, it may be necessary to install HCSR-FCL on more branches. Compared with the bus connection installation scheme, it is not economic relatively. For the installation of HCSR-FCL on the bus connection, the short-circuit current of multiple branches can be limited at the same time. The number of FCLs used is less, and the current limiting cost is lower, but the optimal scheme needs to be obtained by the method of classification enumeration, which is complicated for the optimization configuration of complex grid.
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