Risk-based configuration of current limiters in large scale power systems

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Abstract. The short-circuit current level has become the most prominent constraint for composite power grid. Consequently, it is of unprecedented necessity to adopt specific measures to limit the short-circuit current levels in transmission network planning. A multi-objective model is proposed in this paper to configure current limiting measures. The proposed model is risk-based which considers both the occurrence probabilities and consequence severity levels of short circuit events. NSGA-II is utilized to solve the Pareto proposed model, which provides a Pareto set of optimal current limiting solutions, rather than a single solution. This proposed method effectively enhances both the cost-effectiveness and decision flexibility in current limiting planning.

1. Introduction

The spatial locations of power supply and demand are obviously inconsistent. In China, for example, most of the coal, hydro, wind and solar energy resources are distributed in the western, southwestern, and northern regions. While, more than 70% of energy demand is concentrated in the central and Eastern regions. Consequently, many UHV AC/DC projects been developed to ensure the efficient transmission and absorption of remote power. Globally, driven by the demand of wide-area power allocation, several giant power grids have been developed including the US-Canada grid, the European super grid, the Russian-Baltic grid, etc. [1]. The interconnection of power grids is one of the most significant features of modern power systems.

The key equipment for power system to withstand short circuits is the circuit breakers. With the expansion of power grid scale, the electrical distance between plants and stations is significantly shortened, and the system impedance is declining, resulting in the continuously rising short-circuit currents [2]. The short-circuit current levels have been the most prominent constraint for composite power grid. Moreover, it is of unprecedented importance and necessity to utilize specific measures to limit the short-circuit current levels in transmission network planning. As the three-phase short-circuit currents are generally larger than the single-phase ones, and the three-phase current limiting measures also have the effect of single-phase current limiting, the three-phase short-circuit limiting strategies have received increasing attention [3].

As shown in Figure 1, three-phase short-circuit current limiting measures can be divided into the disconnection type and impedance type. The disconnection measures include network partition and
gradation, bus-bar splitting, open-loop operation for looping, tie line disconnection, etc [3]. The impedance type includes adding Current Limiting Reactor (CLR) [4], Fault Current Limiter (FCL) [5], High Impedance Transformer (HIT) [6], etc.

Faced with numerous current limiting measures, the challenging task for planners is how to select the suitable schemes including the location of the implemented measures as well as the specific capacity or impedance parameters. Traditional current limiting measures are usually calculated and checked one by one for multiple candidate installation locations and available capacities, which is cumbersome, inefficient and subjective [7].

Recently, some allocation methods of current limiters have been developed in the planning stage. Ref. [8] proposed the branch of minimum resistance to guide the installation location of FCLs; In [9], the genetic algorithm (GA) was adopted to optimize the location and resistance of FCLs. Ref. [10] defined the impedance sensitivity factor, and then integrated it with the GA to optimize the impedances of FCLs. Ref. [11] put forward several indices to be satisfied in open-loop operation for electromagnetic looping, including static security and short-circuit current. Ref. [12] proposed a multi-objective configuration model of FCL, CLR, and HIT considering transient stability of power systems.

Generally, the existing studies on optimal configuration of current limiting measures are based on deterministic security criteria, which has not associated with risk perception ability [8-12]. On the contrary, power system faults occur occasionally including the short circuits. If the existing planning methods only focus on the consequences of faults without consideration of their probabilities, it easily leads to the overallocation results of current limiters. Typically, in order to defend against an extremely rare short-circuit event, a lot of current limiting efforts are adopted causing waste of investments.

The risk is defined as the product of event probability and its severity. The NERC published the White Paper Integrated Bulk Power System Risk Assessment Concepts in 2010, which proposed the risk assessment to enhance power dispatching [13]. PJM has introduced risk management into its market operation [14]. Generally, risk-based power system planning and operation are receiving more and more attention.

It is urgent to consider the dual attributes of short-circuit fault including its probability and consequence, and exploit a comprehensive risk-based allocation method of current limiting measures.

2. Model of current limiters
After adopting some assumptions and simplification, an engineering calculation method for three-phase short-circuit current can be given as follows [15]:

![Figure 1. Widely used current limiting measures.](image-url)
Where, \( I_b'' \) is the initial sub-transient current of node \( b \), or the maximum value of fault current. \( V_b(0) \) is the voltage of node \( b \) before the fault. \( Z_{bb} \) is the self-impedance of node \( b \) which can be obtained as the also corresponding diagonal element of nodal impedance matrix \( Z \).

The basic principle of short circuit current limiting is to modify the node impedance matrix. The most common strategy is to configure specific devices such as CLR, FCL and HIT on specific lines.

If the original impendence of line \( l \) between node \( i \) and \( j \) is \( x_{ij} \), the installation of a certain CLR, FCL, or HIT in series to line \( l \) is equivalent to imposing an impedance increment \( \Delta x_l \) to \( x_{ij} \). The corresponding admittance increment of line \( l \) is \( \Delta y_l = -\frac{\Delta x_l}{x_{ij}+\Delta x_l x_{ji}} \). The admittance matrix increment can be expressed as:

\[
\Delta Y = M \times \delta y \times M^T \tag{2}
\]

Where, \( \delta y = [\Delta y_l] \), \( M \) is the line correlation matrix. If line \( l \) is ordinary, then \( M = [0 \cdots 1 -1 \cdots 0]^T \); if \( l \) is a transformer line, \( M = [0 \cdots 1 -k \cdots 0]^T \), \( k \) is the standard ratio reduced to the \( i \) side. If the current limiting measures are implemented on \( n \) lines, the corresponding \( M \) and \( \delta y \) can be denoted as:

\[
M = [M_1 \cdots M_n], \quad \delta y = \begin{pmatrix} \Delta y_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \Delta y_n \end{pmatrix} \tag{3}
\]

Based on the Inverse Matrix Modification Lemma[16], the corresponding impendence matrix increment can be obtained as:

\[
\Delta Z = -ZM \times (\delta y^{-1} + M^T ZM)^{-1} \times M^T Z \tag{4}
\]

If only the admittance of line \( l \) is increased by \( \Delta y_l \) (limiting measure is only implemented on line \( l \)), the nodal impendence matrix increment \( Z \) can be denoted as:

\[
\Delta Z = \frac{(Z_{li}-kZ_{ij})^T(Z_{li}-kZ_{ij})}{Z_{ii}+k^2Z_{jj}-k(Z_{ij}+Z_{ji})+1/\Delta y_l} \tag{5}
\]

In Eq. (5), \( Z_i \) and \( Z_j \) are the column vectors \( i \) and \( j \) in matrix \( Z \). \( Z_{bi}, Z_{bj}, Z_{ji}, Z_{ij} \) and \( Z_{ij} \) are the corresponding elements in \( Z \), respectively. Obviously, the increment of diagonal element \( Z_{bb} \) can be obtained as follows:

\[
\Delta Z_{bb} = -\frac{(Z_{bi}-kZ_{bj})^2}{Z_{ii}+k^2Z_{jj}-k(Z_{ij}+Z_{ji})+1/\Delta y_l} \tag{6}
\]

With the increase of \( Z_{bb} \), the fault current of node \( b \) is reduced correspondingly, which is the principle of impedance type current limiters.

Essentially, the network partition and bus-bar splitting are equivalent to line disconnection, which means to impose an infinite increment \( x_{ij} \rightarrow \infty \) on the line reactance. Therefore, the diagonal element increment \( Z_{bb} \) caused by line \( l \) disconnection can be expressed as:

\[
\Delta Z_{bb} = \lim_{\Delta x_l \rightarrow \infty} \left( -\frac{(Z_{bi}-kZ_{bj})^2}{Z_{ii}+k^2Z_{jj}-k(Z_{ij}+Z_{ji})+\frac{\Delta x_l x_{ij}}{Z_{ii}+\Delta x_l x_{ij}}} \right) = -\frac{(Z_{bi}-kZ_{bj})^2}{Z_{ii}+k^2Z_{jj}-2kZ_{ij}x_{ij}} \tag{7}
\]

With the increase of \( Z_{bb} \), the fault current of node \( b \) is reduced, which is the principle of disconnection type current limiting measures.

3. Assessment of nodal short circuit risk

The short circuit risk level of node \( i \) is formulated as the product of occurrence probability and severity level of short circuit event at node \( i \).

\[
Risk_i = \left[ \phi \left( \frac{\nu_i}{z_i}, Th_i \right) \lambda_o \right] p_i \tag{8}
\]
In Eq. (8), $V_i$ and $Z_{ii}$ are the voltage and self-impedance of node $i$, respectively. $Th_i$ is the current threshold of node $i$, which is measured as the interruption limit of breaker at node $i$. $\lambda_o$ is the penalty coefficient (set as 100 in this paper). The penalty operator $\phi$ is operated as:

$$\phi(X_1, X_2) = \begin{cases} X_1 - X_2, & \text{if } X_1 \geq X_2 \\ 0, & \text{if } X_1 \leq X_2 \end{cases}$$

(9)

Figure 2. Factors of short circuit probability.

The key of short-circuit risk assessment is to quantify the fault probability. Based on plenty of existing literatures and engineering practices, the nodal short-circuit probabilities are determined by various factors. Shown as Figure 2, the internal factors include the insulation level and operation years of components. Short circuits may also be caused by external forces such as strong wind and tree collapse. In this paper, a calculation method of nodal short circuit probability is proposed.

$$p_i = y_o \cdot a_{gi} \cdot v_{ei} \cdot w_{ei}$$

(10)

Where, $y_o$ is the initial short circuit rate of the equipment of interest which is determined by the insulation level. $a_{gi}$ represents the amplification factor of short-circuit rate due to the increasing of operation years. $v_{ei}$ and $w_{ei}$ are the vegetation score (vegetation density) and weather score (extreme weather frequency) of node $i$, respectively, which are both scaled to 1~10. Specifically, the denser the vegetation or the more frequent the extreme weather, the higher the corresponding scores.

4. Multi-objective allocation model for current limiters

The objective functions of current limiter configuration include the cost objective and the risk assessment objective.

The objective function $F_1$ measures the economy of the current limiting measures which is defined as the total cost of the adopted current limiters.

$$F_1 = \sum_{s \in \Gamma} u_s (k_{us} + k_{ws}w_s)$$

(11)

In Eq. (11), $\Gamma$ is the set of current limiting measures. $u_s$ is the binary control variable indicating whether the measures are put into operation. $u_s = 1$ means the line is disconnected or the FCL of interest is configured. $u_s = 0$ means the limiter is excluded. $k_{us}$ and $k_{ws}$ are the fixed and variable cost coefficients of current limiting measure $s$; $w_s$ is the continuous variable which represents the specific parameters of the current limiting equipment, including the reactance of CLR, FCL, and the voltage percentage of HIT.

The objective function $F_2$ is defined as the system risk level, which is formulated as the sum of nodal risks.

$$F_2 = \sum_i Risk_i$$

(12)

The inequality constraints for the optimal allocation of current limiting are as follows:

$$V_i^{\min} \leq V_i \leq V_i^{\max}, i = 1, 2, \ldots, n$$

(13)

$$F_l \leq F_l^{\max}, l = 1, 2, \ldots, L$$

(14)
where, Eq. (13) is the nodal voltage constraint. \( V_{i}^{\text{min}} \) and \( V_{i}^{\text{max}} \) are upper and lower limits for voltage of node \( i \), respectively. Eq. (14) is the power flow constraint, in which \( F_{l}^{\text{max}} \) is the upper limit of flow at branch \( l \). Eqs. (15) and (16) are the range constraints of decision variables.

5. Solution method

Due to the high dimension, nonconvex and nonlinear characteristics of the proposed multi-objective model, NSGA-II, an efficient evolutionary intelligence algorithm is introduced to search the feasible current limiting scheme. The detailed implementation procedure of NSGA-II can be found in [17], a brief description of NSGA-II procedure is shown in Figure 3.

![Flow chart of NSGA-II procedure.](image)

The population is initialized as usual and then sorted based on non-domination levels into fronts. The first front is a set of chromosomes being completely non-dominant or not dominated by any other individuals in the current population, the second front being dominated by the chromosomes in the first front only and the front goes so on. In addition to front rank, crowding distance is calculated for each chromosome, which measures how close a chromosome is to its neighbors. Large average crowding distance results in better diversity in the population. Parents are selected by using Binary Tournament Selection based on operator \(<_n\). \(<_n\) is based on front rank and crowding distance as follows [17]:

a. The chromosome with the higher front rank value is greater than the other regardless of crowding distance, and is selected;

b. The chromosome with the larger crowding distance is greater than the others located in the same front, and is selected.

6. Case studies

The actual transmission network of Jiangsu province in China is utilized to verify the proposed method. The system consists of 82 nodes, and the topology is shown in Figure 4. T and L represent transformer and ordinary lines, respectively. If the current breaking capacities of the circuit breakers are all 60 pu., then there are 12 nodes whose short circuit currents violate the thresholds. The top three nodes as well as the specific fault current values are \( I_{27} = 97 \text{pu}, \ I_{28} = 141 \text{pu}, \ I_{32} = 110 \text{pu} \). The equipment insulation parameters, operation years, climate and vegetation conditions of nodes are
Figure 4. Topology of the realistic test system.

NSGA-II is adopted to optimize the current limiting scheme of the test system. After 100 generations of evolution, all Pareto solutions in the final generation are illustrated in Figure 5. As can be seen, an obvious mutual exclusion characteristic exists between economy and security of the system. With the increase of current limiting scheme investment, the short-circuit risk of the system decreases significantly. In the obtained 10 Pareto solutions, solution 10 achieves the complete elimination of short circuit risk, which means fault currents of all the nodes are successfully limited within the given thresholds. While the investment of solution 10 is the highest. With the obtained Pareto solution set, the planners can select the final current limiting scheme according to different risk preferences, which provides significant flexibility.

Figure 5. The obtained Pareto current limiting schemes.
If there are no clear preferences, some weighted decision methods can be used to select the optimal solution. Ref. [18] proposed a membership-based weighted decision method. With this method, solution 6 is identified as the suggested one, whose specific configuration scheme of current limiting measures is illustrated in Figure 6.

Figure 6. The specific current limiting measures of solution 6.

7. Conclusions
A multi-objective risk-based model is proposed in this paper as an effective analysis tool for current limiting measures allocation in composite power systems. The proposed model is risk-based which considers both the occurrence probabilities and consequence severity levels of short circuit events. This can effectively avoid the waste of investment in current limiting planning. A NSGA-II is introduced to solve the Pareto proposed model, which provides a Pareto set of optimal current limiting solutions, rather than a single solution. This method enables decision-makers to select their ideal schemes according to different preferences and thus achieves a great flexibility.

The short-circuit rates of electrical components are associated with manufacturing standards, operation life, climate state, and so on. The utilized fault rate model in this paper is relatively preliminary. In the future study, more historical data need to be obtained to establish a rigorous short-circuit probability model with multiple factors.

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