Optimum Short Circuit Current Limiter Deployment Using Immune-PSO Algorithm

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Abstract—The optimum of short circuit current limiter deployment (SCCLD) is a 0-1 mixed integer programming problem. It is non-continuous, non-convex and nonlinear. Ordinary mathematic optimization can hardly solve it. In this paper, the sensitivity factor was defined to choose better candidates for active current-limiting measure installations as to reduce bus fault currents. And the integrated measures deployment is solved by a discrete particle swarm optimization algorithm with immune (IA-DPSO). The results of IEEE 39-bus system in New England are provided to validate the possible applications of the proposed method.

1. Introduction
As the increasing demand for power, electric power system expands and power grid become more and more complicatedly interconnected. As a result, the level of short-circuit current grows increasingly higher, and at many points it may exceed the short-circuit current ratings of circuit breakers. It is very dangerous, because it may damage system equipment, especially, for those with continuous growth in network size and power demand[1]-[4]. Thus the reduction of short-circuit current becomes one of the most urgent problems in power systems.

Methods for the present time to reduce 3-phase short-circuit include voltage-grading, area separation, bus-splitting, using high-impedance transformers, installing current limiting reactors or various fault current limiters(FCLs), et al. Human experience to deploy above current-limiting measures is obviously inappropriate.

In reference [1], an optimization strategy to limit short circuit current was proposed. It considers several types of current-limiting measures and gives the incremental of $Y_{bus}$ according to the measures. And finally a mathematic model for optimizing those measures is formed. But the model is very preliminary. This paper will improve the model according to the actual power grid system.

In reference [2] and [3], a discrete particle swarm optimization algorithm (DPSO) was proposed to solve the problem. It has achieved some ability in solving the complex problem which is non-continuous, non-convex and nonlinear. But still the rate of success is very low. We will improve the algorithm with immune to keep the diversity of particle to achieve global optimum. And a search space reduction technique will also be introduced to prevent the algorithm from dimension disaster. The efficiency of the proposed method is shown by examples.

2. Model of SCCLD Optimization
The decision-making variables of the problem include the 0-1 variable $u$, which is to decide the deployment of a certain current-limiting measure and the variable $v$ to decide the reactance of a reactor
or a high-impedance transformer. Actually, the reactance of a reactor or a high-impedance transformer should be considered to be an integer. When the decision variables vary, the system configuration will change and so will the system state variable such as power flows and short-circuit current, etc. Thus the problem is a mixed integer programming problem and can be expressed as follows:

\[
F(u, w, x) = \min \sum_{s=1}^{N_s} \frac{1}{P_s} (A_s + B_s w_s)
\]

s.t.

\[
\begin{bmatrix}
\Delta P

\Delta Q
\end{bmatrix} =
\begin{bmatrix}
J_{po} & J_{pr} \\
J_{qr} & J_{qf}
\end{bmatrix}
\begin{bmatrix}
\Delta V

0
\end{bmatrix}
\]

\[
\Delta V_i \leq V_i \leq V_i^\text{up}, i = 1, 2, ..., N
\]

\[
|F_l| \leq \bar{F}_l, l = 1, 2, ..., L
\]

\[
\max(I_i(i), I_{i(1)}) \leq I_{i(1)}, i = 1, 2, ..., N
\]

\[
\underline{v}_i \leq v_i \leq \overline{v}_i, \text{ and } v_i \text{ is integer}
\]

\[
\forall u_s \in \{0, 1\}
\]

where \(N_s\) is the total number of current-limiting strategies to take account. \(P_s\) is the preferences of measures. Equation (15) is the power flower equation, \(\Delta V_i\) is the upper bound and the low bound of voltage at bus \(i\) \((V_i)\). \(F_l\) is the power flower of line \(l\), and \(\overline{F}_l\) is the upper bound of it. \(I_i(i)\) is the 3-phase short-circuit current at bus \(i\) while \(I_{i(1)}\) is the 1-phase short-circuit current. \(\underline{v}_i\) is the lower bound of \(v_i\) and \(\overline{v}_i\) is the upper bound.

### 3. Sensitivity Factor Calculation

In large power grid system, it is hard to determine optimal number, locations and parameters for current-limiting measures. Thus makes the number of variables very big, and makes the problem complicated. In this paper, we will introduce sensitivity factor to select the locations and reduce the number of variables of current-limiting measures.

When the admittance of a branch from node \(i\) to node \(j\) increases \(\Delta y_{ij}\), the \(Z_{bus}\) of system increases as follows:

\[
\Delta Z = -\frac{(Z_j - kZ_i)^T (Z_j - kZ_i)}{\Delta y_{ij} + k^2Z_j + 2kZ_j}
\]

where \(Z_i\) and \(Z_j\) is the \(i^{th}\) and \(j^{th}\) column vector of \(Z_{bus}\). \(k\) is the ratio of a transformer from \(j\) to \(i\) and \(k = 1\) for a line branch. \(Z_{ii}, Z_{jj}\) and \(Z_{ij}\) are the elements of \(Z_{bus}\).

If a line is open, then \(\Delta y_{ij} = -y_{ij}\), that the change of \(Z_{bus}\) according to \(b\) will be:

\[
\beta_{\phi(b)} = \Delta Z_{ab} = -\frac{(Z_{rb} - Z_{by})^T}{-x_q + Z_{by} + Z_{rb} - 2Z_{by}}
\]

\(\beta_{\phi(b)}\) is the incremental of impedance at node \(b\) when line \(i-j\) opens. For all buses whose current are too big, that the sensitivity factor \(\beta\) is calculated as follows:

\[
\beta_{\phi} = \sum_{s=1}^{N_s} \left( I_{s(b)} \right)^T \beta_{\phi(s)}
\]

where \(I_{s(b)}\) is the current of bus \(b\), and \(\bar{T}_s\) is the upper bound of \(I_{s(b)}\). \(\gamma\) is an adjustment coefficient. \(\beta_{\phi}\) is to choose the better candidate line for opening.

As to the current-limiting measures such as CLR, FCL and HIT, differential is used, that is:
\[ a_{(i,j)} = \lim_{\Delta x_i \to 0} \frac{1}{\Delta x_i} \left( \frac{Z_{i,j} - k Z_{i,j}}{x_{i,j}} \right)^2 \]  

(11)

where \( x_{i,j} \) is the impedance of line \( i-j \), and \( \Delta x_{i,j} \) is the incremental of it.

For all buses whose current are too big, the sensitivity factor \( \alpha \) is calculated as follows:

\[ \alpha_{(i,j)} = \sum_{b \in \mathcal{I}} \left( \frac{l_{b}}{f_{b}} \right)^\gamma a_{(i,j)} \]

(12)

\( \alpha_{(i,j)} \) is to decide the better candidate for above current-limiters.

4. Discrete Particle Swarm Optimization Algorithm with Immune (IA-DPSO)

Particle swarm optimization algorithm (PSO) is a swarm intelligence algorithm that is not largely affected by the scale and non-linearity of the problem. It is simple and has fast convergence, but for complex problems it is always too easy to fall into a local extreme. Immune algorithm (IA) has very good features in keep population diversity and can find the global optimum by probability. Thus we introduce the clone operator and the mutation operator from IA into the discrete PSO, and a new algorithm IA-DPSO is formed to solve the problem.

4.1. Search Strategy and Discrete Strategy of DPSO Algorithm

In the simplified PSO algorithm, each solution is called a “particle”. Each particle has it position, velocity, and fitness value. Particles fly through the n-dimensional space by learning from the historical information of the swarm population. For this reason, particles are inclined to fly towards better search area over the course of evolution[5].

Let \( m \) denote the swarm size represented as \( \mathbf{X} = [x_1, x_2, ..., x_n] \). Then each particle in the swarm population has the following attributes: a current position represented as \( \mathbf{x}' = [x'_{11}, x'_{12}, ..., x'_{1n}] \); a current velocity represented as \( \mathbf{v}' = [v'_{11}, v'_{12}, ..., v'_{1n}] \); a current personal best position represented as \( \mathbf{x}_{pb} = [x_{pb1}, x_{pb2}, ..., x_{pbn}] \); and a current global best position represented as \( \mathbf{x}_{gb} = [x_{gb1}, x_{gb2}, ..., x_{gbn}] \). Assuming that the function \( f \) is to be minimized, the velocities of \( i \)th particle is updated as follows:

\[ \mathbf{v}'_{i+1} = K \left( \mathbf{v}'_{i} + c_1 r_1 (\mathbf{x}_{pb} - \mathbf{x}'_{i}) + c_2 r_2 (\mathbf{x}_{gb} - \mathbf{x}'_{i}) \right) \]

(13)

where \( K \) is the inertia weight which is a parameter to control the impact of the previous velocities on the current velocity; \( c_1 \) and \( c_2 \) are acceleration coefficients while \( r_1 \) and \( r_2 \) are uniform random numbers between \([0,1]\).

The position of the \( i \)th particle is updated as follows:

\[ \mathbf{x}'_{i+1} = \mathbf{x}'_{i} + \mathbf{v}'_{i+1} \]

(14)

As the decision-making variables of the problem are integers, the position find by PSO should be discrete. In a discrete strategy, the velocity of the \( d \)th dimension of the \( i \)th particle is updated as follows when the velocity calculated from a search strategy is at bounds:

\[ v_{id} = \begin{cases} \left\lfloor v_{id} \right\rfloor, & \text{if } \min \leq S(v_{id} - \left\lfloor v_{id} \right\rfloor) \\ \left\lfloor v_{id} \right\rfloor, & \text{else} \end{cases} \]

(15)

where \( \left\lfloor v_{id} \right\rfloor \) is the nearest integer smaller than \( v_{id} \), \( \text{rand} \) is a random number uniformly distributed in interval \([0,1]\) and \( S(x) \) is a sigmoid function:

\[ S(x) = \frac{1}{1 + e^{-x}}, x \in [0,1] \]

(16)

When the original velocity calculated from a search strategy is out of bound, the velocity is set to be at the lower bound or the upper bound:
4.2. Clone Strategy and Mutation Strategy of IA

In IA algorithm, the probability of clone operator and mutation operator is related both to the diversity of system and the affinity between antigen and antibody\cite{6}.

The information entropy of \(j\)th particle is defined as follows:

\[
H_j(N) = \sum_{i=1}^{M} p_{ij} \log p_{ij}
\]

where \(p_{ij}\) is the probability that \(i\)th allele comes out at the \(j\)th gen. \(N\) is the total number of population. And the diversity of population can be evaluated as:

\[
H(N) = \frac{1}{M} \sum_{j=1}^{M} H_j(N)
\]

Figure 1 Application of IA-DPSO to optimize current limiting strategies

The similarity of tow antibodies can be evaluated as:

\[
A_{s}(b,d) = 1/[1 + H(2)]
\]

The affinity between antigens and antibodies is defined as follow

\[
A_{a}(b) = 1/[1 + \frac{\text{fit}_b}{\sum_{b=1}^N \text{fit}_b}]
\]

where \(\text{fit}_b\) is the fitness of antibodies \(b\).

The expectations of particle \(b\) is defined as

\[
E(b) = \frac{A_{a}(b)}{C(b)}
\]

where \(C(b)\) is the antibody concentration of particle \(b\).

The probability of clone varies to the affinity and similarity of a particle, that is:
This clone operator will choose the better antibodies and keep the population diversification, too. The probability of mutation is:

\[ P_m = \frac{1}{1 + H(N)} P_0 \]  

(24)

where \( P_0 \) is constant. This probability will be larger when the diversification of population is lower. When a particle is chosen for mutation, its position will change as follows:

\[ x'_d = \text{rand}\{x_d, x_d + 1, ..., x_d - 1, x_d\} \]  

(25)

where \( x_d \) is the lower bound of \( x_d \), while \( x_u \) is the upper bound. \( \text{rand} \) means to take a random number.

The flow chart of applying IA-DPSO to optimize current limiting strategies is shown in Figure 1.

5. Numerical Example

A 39-bus power system in New England was used to show the effectiveness of the proposed method. The system has 34 line branches and 12 transformer branches, and 3 bus branches as shown in Figure 2. The basic voltage of the system except power generators is 242 kV. The short-circuit current ratings of switchgear is 70 pu. Three bus nodes are over the level, and they are bus 2, bus 16, and bus 39. The short-circuit current is 74.45 pu at bus 2, 73.89 pu at bus 16 and 99.95 at bus 39. Bus-splitting has so many shortcomings, so it is not assumed in this system, but a CLR in a bus-bar is allowed.

![Bus-splitting diagram of New England 10-unit 39-bus system](image)

Figure 2 Bus-splitting diagram of New England 10-unit 39-bus system

The cost coefficient is defined as follows:

| coefficient | Line opening | CLR (line/bus) | HIT | NGR |
|-------------|--------------|----------------|-----|-----|
| A           | 60           | 625/750        | 100 | 30  |
| B           | 25/50        |                | 50  | 1   |

The transient impedance \( X'_d \) of generations is shown in Table 2.
Table 2  The Transient Impedance $\chi'_g$ of Generations

| Gen number | Bus number | $\chi'_g$ | Gen number | Bus number | $\chi'_g$ |
|------------|------------|----------|------------|------------|----------|
| 1          | 39         | 0.0128   | 6          | 35         | 0.0450   |
| 2          | 31         | 0.0627   | 7          | 36         | 0.0441   |
| 3          | 32         | 0.0478   | 8          | 37         | 0.0513   |
| 4          | 33         | 0.0392   | 9          | 38         | 0.0513   |
| 5          | 34         | 0.1188   | 10         | 30         | 0.0279   |

The sensitivity factor according to line open is computed and show in Table 3. As line 1-2 has the same sensitivity factor as line 1-39, we can choose either of them.

Table 3  The Sensitivity Factor According to Line Open

| Line     | $\beta_2$ | $\beta_{16}$ | $\beta_{39}$ | $\beta_i(\gamma=0.5)$ |
|----------|-----------|--------------|--------------|-----------------------|
| 16-17    | 0.0014127 | 0.0045997    | 0.0000349    | 0.0062244             |
| 2-3      | 0.0043083 | 0.0012629    | 0.0000140    | 0.0057574             |
| 1-2      | 0.0025012 | 0.0002304    | 0.0011778    | 0.0042236             |
| 1-39     | 0.0025012 | 0.0002304    | 0.0011778    | 0.0042236             |

The sensitivity factor according to add the impedance of a branch is show in Table 4. 3 bus-bar and 1 transformer branch and 3 line branch are active.

Table 4  The Sensitivity Factor for Adding Branch Impedance

| branch    | $\alpha_2$ | $\alpha_{16}$ | $\alpha_{39}$ | $\alpha_i(\gamma=0.5)$ |
|-----------|------------|--------------|--------------|-----------------------|
| Bus 39    | 0.004547   | 0.000028     | 0.250015     | 0.303473              |
| Bus 16    | 0.000913   | 0.288525     | 0.000220     | 0.297638              |
| Bus 2     | 0.252371   | 0.023407     | 0.003495     | 0.288502              |
| 16-17     | 0.028163   | 0.091698     | 0.000696     | 0.124089              |
| 2-3       | 0.082301   | 0.024125     | 0.000267     | 0.109985              |
| 2-30      | 0.085252   | 0.010597     | 0.002953     | 0.102339              |
| 2-25      | 0.066881   | 0.000005     | 0.001856     | 0.071199              |

If we consider 3 line branches to be the candidate branch to be open, and 6 branches to be the candidate branch to increase its impedance by adding a CLR or FCL, and using a HIT, and so on. Then the candidate line to be open are line 16-17, 2-3, 1-2 or 1-39. Bus 39, 16, bus 2 and line 16-17, 2-3 are the candidate location to use a CLR or FCL. And transformer 2-30 considers to use a HIT.

The parameter of IA-DPSO is set as follows: $N=50$, $c_1=c_2=1.05$, $K=0.9$, $\lambda=0.93$, $P_0=1$ and $T_{max}=100$. Running the program for 20 times, the optimum solution is that bus 39 to add a 25 $\Omega$ CLR and the same time to open line 1-2 (or line 1-39) and line 2-3. The maximum fault current of the system is down to 69.84 pu and voltage amplitude of each node is limited to 0.95~1.05. The total cost of this strategy is 1620. Cost curve obtained by IA-DPSO is shown in Figure 3.
6. Conclusions
In this paper, we have proposed a method based on mathematical optimization model to solve the problem of short circuit current limiting. The mathematical model is a mixed integer programming problem and for a large loop system, it is very hard to solve. The proposed method can be used to find the minimum number of active current-limiting measures and select the most efficient locations. It makes the problem easy to solve and an IA-DPSO algorithm was proposed to solve the problem. The numerical results show that IA-DPSO has good convergence in search for the optimal solution. The proposed method makes it easier and more scientific to find an optimal strategy to limit system short-circuit current.

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