Pareto optimal allocation of resistive-type fault current limiters in active distribution networks with inverter-interfaced and synchronous distributed generators

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Abstract
To efficiently reduce the fault currents of active distribution networks (ADNs), this paper proposes a novel methodology for Pareto optimal allocation of resistive-type fault current limiters (R-FCLs). The proposed approach enables to simultaneously optimize the number, location, and size of the R-FCLs in the ADNs with inverter-interfaced and synchronous distributed generators (DGs). The sensitivity analysis is introduced to rank candidate locations, and a constrained multiobjective function is created to minimize the cost of the R-FCLs and the fault currents of the ADNs. An improved multiobjective particle swarm optimization (MOPSO) algorithm and a multiobjective artificial bee colony (MOABC) algorithm are designed to obtain the Pareto optimal solution set. The proposed approach is verified using the modified IEEE 33-node and 69-node distribution systems, where both centralized and dispersed access of DGs are considered. The numerical results demonstrate that: (a) The fault currents in all nodes of the two testing systems are limited to the permissible levels using the least capital cost of the R-FCLs, and (b) the improved MOPSO outperforms the MOABC to achieve a better Pareto front and decrease the number of iterative computation. In consequence, the feasibility and superiority of the proposed approach are well validated.

Keywords
active distribution networks, distributed generators, multiobjective optimization, Pareto optimal allocation, resistive-type fault current limiters

1 INTRODUCTION
To more flexibly accommodate an increasing number of inverter-interfaced and synchronous distributed generators (DGs), active distribution networks (ADNs) have been introduced and attracted considerable attention.1-5 Currently, one of the most critical challenges regarding the development of ADNs is to enhance the robustness against short-circuit faults, and there is an urgent demand to efficiently suppress the fault currents of ADNs.6

Applying fault current limiters (FCLs) in ADNs can be thought of as a very direct and promising solution.7-12 Technically, a FCL shows little impedance without disturbing the normal operation, and once a short-circuit fault is detected,
the FCL will be fast triggered to insert its current-limiting impedance into main system. Considering the architecture of ADNs, FCLs may have multiple candidate locations to add their impedances into the paths of fault currents. For taking full advantage of FCLs, the key point is to find the optimal placement, proper rating, and number of FCLs. Herein, it is of significance to determine a feasible methodology for the optimal allocation of FCLs.

1.1 Literature review

Currently, some contributive researches on optimizing FCLs have been done, and a comprehensive literature review is as follows.

In Ref. the system stability is selected as a single-objective optimization function, and the optimal placement of FCLs is studied. In Ref. the optimal power flow in a traditional electrical grid is handled concerning fault current constraints, and the optimal allocation of inductive FCLs based on genetic algorithm is investigated. In Ref. aiming at the distribution systems with synchronous DGs, the recloser-fuse coordination is realized by the optimal configuration of FCLs. In Ref. FCLs are optimized in mesh networks, and the distinguishable contribution is that the predetermined installation sites and random scanning techniques do not restrict the approach. In Ref. considering different material laws and overall protection behaviors, the optimal employment of superconducting FCLs in standard networks is discussed. In Ref. an optimal FCL study containing economic analysis is done, and improving reliability and reducing losses are formulated as the objectives. Recently, there are some new research trends to optimize FCLs, and two categories are roughly classified.

1. Using multistage/joint optimization and combination of multiple algorithms.

In Ref. a two-stage placement approach is proposed to optimize FCLs. Stage I is to rank feasible solutions and seek out an optimal FCL location. Stage II is to optimize the FCL capacity. In Ref. the joint optimization of DGs and FCLs in distribution networks is carried out. In Ref. a combination of genetic algorithm and linear programming is used to find the minimum capacity of FCLs and optimal setting of the relay protection system. In Ref. scholars propose the combined cuckoo optimization algorithm and LP to coordinate the protective relays and search the optimum size of FCLs.

2. Exploring Pareto optimal allocation and adopting FCLs in DC power systems.

In Refs. scholars explore the Pareto optimal allocation of FCLs basing multiobjective firework algorithm and immune algorithm to address contradictory objectives, and the proposed optimal countermeasures are helpful for allocating FCLs to achieve various current-limiting features. In Ref. aiming at two testing systems with conventional generators, the Pareto optimal allocation of FCLs is conducted for network reliability improvement and fault current inhibition. In Refs. DC power systems are selected to accommodate FCLs, and the optimal application of FCLs in the looped-type DC microgrids and DC distribution networks is demonstrated.

From the literature review, it is revealed that more efforts are to optimize FCLs in standard electric networks with large-scale power plants, but there is limitable attention on optimizing FCLs in active distribution systems with different DGs. In a sense, the main shortcoming of the existing works is that they have no regard for how different types and access modes of DGs can affect the optimal allocation of FCLs. Technically, inverter-interfaced and synchronous DGs have different contributions in increasing the fault currents. Even if the number and capacity of these DGs are constant, different access modes will bring the change in the fault current distribution characteristics.

1.2 Contributions of this paper

The purpose of this paper was to propose a novel methodology for Pareto optimal allocation of resistive-type fault current limiters (R-FCLs) in the ADNs containing IIDGs and synchronous DGs. The main contributions and novelties of this paper are summarized as follows.

1. Propose a multiobjective approach for optimizing the R-FCLs in the ADNs, where inverter-interfaced and synchronous DGs are accessed.
2. Minimize two different and conflicting objectives simultaneously to search optimal placement and size of the R-FCLs without using pre-assumptions.
3. Design an improved multiobjective particle swarm optimization (MOPSO) algorithm and a multiobjective artificial bee colony (MOABC) algorithm to solve the studied problem.
4. Apply the proposed approach in two different scales of testing systems, where both centralized and dispersed access of DGs are considered to carry out the comparative analysis.

1.3 Organization of this paper

The rest of the paper is organized as follows. Section 2 presents the fault current calculation and the impacts of the R-FCLs on the ADNs. In Section 3, the formulation of the optimization problem among the constraints governing the studied system is stated. Section 4 elaborates the Pareto
optimization procedure based on the improved MOPSO and MOABC algorithms. In Section 5, the performance evaluation of the proposed approach is done. Section 6 conducts technical discussions on the optimization techniques considering protective relay coordination and sensitivity analysis methods. Section 7 summarizes the main conclusions and explores the follow-on work.

2 | FAULT CURRENT CALCULATION AND INFLUENCE OF R-FCL

2.1 | Fault current analysis of the ADNs with DGs

Figure 1(A) shows the fault analysis circuit of the ADNs with inverter-interfaced and synchronous DGs, and the most serious three-phase fault is implemented. For the synchronous DG and the main system coupled to the ADNs, $E_s$, $E_{s-DG}$, $X_s$, and $X_{s-DG}$ denote their equivalent electromotive forces and impedances, respectively. The IIDG is equivalent to one current source with the output of $I_{IIDG}$. $Z_{L1}$, $Z_{L2}$, ..., $Z_{Ln}$ are the load impedances, and $U_k$ is the voltage over the fault site $k$.

According to the superposition principle, the fault analysis circuit can be divided into normal component and fault component circuits, which are shown in Figure 1(B) and Figure 1(C), respectively. Therefore, the voltage-current equation can be written as follows:

$$
\begin{bmatrix}
\dot{U}_1 \\
\vdots \\
\dot{U}_n
\end{bmatrix}
= \begin{bmatrix}
U_{i(0)} \\
\vdots \\
U_{n(0)}
\end{bmatrix}
+ \begin{bmatrix}
Z_{i1} & Z_{i2} & \cdots & Z_{in} \\
\vdots & \vdots & \ddots & \vdots \\
Z_{n1} & Z_{n2} & \cdots & Z_{nn}
\end{bmatrix}
\begin{bmatrix}
0 \\
\vdots \\
-1_k
\end{bmatrix}
= \begin{bmatrix}
U_{i(0)}-Z_{ik}I_k \\
\vdots \\
U_{n(0)}-Z_{nk}I_k
\end{bmatrix}$$

(1)

where $U_i$ ($i = 1, 2, \ldots, n$) is the node voltage, whose normal component is signified as $U_{i(0)}$, $Z_{ii}$ is the impedance matrix's diagonal impedance; and $I_k$ is the current in the fault site $k$. 

FIGURE 1 Fault analysis diagram of the active distribution networks with inverter-interfaced and synchronous DGs. (A) Equivalent circuit, (B) normal component circuit, and (C) fault component circuit.
For the metallic short-circuit fault, \( U_e = 0 \) is obtained, and the fault current \( I_k \) will be expressed as follows:

\[
\dot{U}_{k(0)} - Z_{kk} I_k = 0 \Rightarrow I_k = \frac{\dot{U}_{k(0)}}{Z_{kk}}
\]  

(2)

Therefore, it is crucial to determine the voltage \( \dot{U}_{k(0)} \) for solving the fault current Equation (2). In accordance with Figure 1(B), \( \dot{U}_{k(0)} \) can be derived as follows:

\[
\dot{U}_{k(0)} = \begin{bmatrix} Z_{k1} & \cdots & Z_{kk} & \cdots & Z_{kn} \end{bmatrix} \begin{bmatrix} I_{1-s} \\ \vdots \\ I_{k-s} \\ \vdots \\ I_{n-s} \end{bmatrix} = \sum_{i=1}^{n} Z_{ki} I_{i-s}
\]  

(3)

where \( I_{i-s} \) \((i = 1, 2, \ldots, n)\) represents the current supplied by the power source which is coupled to node \( i \). There are three basic situations: (a) If no source is connected, \( I_{i-s} = 0 \). (b) If the main system or the synchronous DG is connected, it is achieved that \( I_{i-s} = E_i/X_i \) or \( I_{i-s} = E_{i-DG}/X_{i-DG} \). (c) If an IIDG is accessed, \( I_{i-s} = I_{IIDG} \) = \( k_{oc} I_{IIDG-rate} \) where \( k_{oc} \) is the coefficient to describe the ratio of the IIDG’s fault current to the rated current \( I_{IIDG-rate} \). In general, the range of \( k_{oc} \) is 1.2–1.5. 

2.2 Influence of the R-FCL on fault current

In this study, the resistive-type FCL based on high-temperature superconducting materials is adopted. The R-FCL owns many unique superiorities, including automatic trigger, compact structure, and preferable current-limiting behavior. It operates in the superconducting status without disturbing the system’s normal operation. Only if the fault current exceeds the critical threshold, the quench phenomenon will be caused, and the R-FCL will show the current-limiting resistance \( z_{FCL} \). Figure 2 shows the transient response of a typical R-FCL, whose mathematical equation is given by:

\[
z_{FCL} = \begin{cases} 0 & (t < t_{qs}) \\ R_{ns} \left[ 1 - \exp \left( -\frac{t - t_{qs}}{\tau} \right) \right]^{1/2} & (t_{qs} \leq t < t_{fr}) \\ a_1 (t - t_{fr}) + b_1 & (t_{fr} \leq t < t_{sr}) \\ a_2 (t - t_{sr}) + b_2 & (t_{sr} \leq t < t_{cr}) \end{cases}
\]

where \( R_{ns} \) represents the resistance of the R-FCL; \( \tau \) signifies the time constant; \( t_{qs}, t_{fr}, t_{sr}, \) and \( t_{cr} \) are the times of the quench starting, the first-stage recovery, the secondary-stage recovery, and the completed recovery, respectively. The coefficients \( a_1 - a_2 \) as well as \( b_1 - b_2 \) are to define different slopes and turning points of the resistance lines.

Figure 3 shows the schematic circuit of a R-FCL installing at branch \( kj \). From the figure, the function of the R-FCL can be equivalent to adding an impedance \( z_F \) in parallel with the original branch impedance \( z_{kj} \). Here, \( z_F \) is formulated as follows:

\[
z_F = (-z_{kj}) \parallel (z_{kj} + z_{FCL}) = \frac{-z_{kj} (z_{kj} + z_{FCL})}{z_{FCL}}
\]

(5)

Due to the introduction of \( z_F \), a modification \( \Delta Z_{ii} \) should be implemented in the original impedance matrix \( Z_{ii} \). The expression \( \Delta Z_{ii} \) is derived as follows:

\[
\Delta Z_{ii} = -\frac{(Z_{ij} - Z_{ik})^2}{Z_{kk} + Z_{jj} - 2Z_{kj} + z_F}
\]

(6)

Consequently, the impedance matrix is updated as \( Z_{ii}' \), which is given by:

\[
Z_{ii}' = Z_{ii} + \Delta Z_{ii} = Z_{ii} - \frac{(Z_{ij} - Z_{ik})^2}{Z_{kk} + Z_{jj} - 2Z_{kj} + z_F}
\]

(7)

Aiming at the ADNs, the fault current calculation can be performed in terms of the node voltage and the updated impedance matrix. In this study, the action criteria of the R-FCL is designed as that once the fault current in a branch exceeds 3.5 times of the nominal level, the R-FCL in this branch should be immediately activated. It means each branch may have its own sensitivity for accommodating the R-FCL. For the purpose of more efficiently sorting the candidate locations, the sensitivity computation and ranking operation are

\[\text{FIGURE 2} \quad \text{Mathematical modeling of the resistive-type FCL}\]

\[\text{FIGURE 3} \quad \text{Schematic circuit of a R-FCL installing at branch kj}\]
taken into consideration. Here, the sensitivity $\eta$ is defined as follows:

$$\eta = \frac{dZ'_u}{dZ_{\text{FCL}}\bigg|_{Z_{\text{FCL}}=0}} = \frac{(Z_{ij} - Z_{ik})^2}{\varepsilon_{kj}}$$ \quad (8)

If a branch has a larger $\eta$, it implies that the R-FCL in this branch can potentially offer a more obvious effect on $Z'_u$ and bring a better current-limiting performance.

3 | PROBLEM FORMULATION OF R-FCL OPTIMAL ALLOCATION

3.1 | Capital cost of the R-FCLs

The first objective function is to minimize the capital cost of the R-FCLs, and that could be realized by adopting the most reasonable number of the R-FCLs with the minimum current-limiting impedances. The objective function $F_1$ and its constraints are expressed as follows:

$$F_1 = mN_{\text{FCL}} + p \sum_{i=1}^{N_{\text{FCL}}} z_{\text{FCL-N}} + F_c$$ \quad (9)

$$F_c = c \sum_{i=1}^{n} \max\{I_{i-\text{FCL}} - I_{\text{max}}, 0\}$$ \quad (10)

$$N_{\text{min}} \leq N_{\text{FCL}} \leq N_{\text{max}}$$ \quad (11)

$$z_{\text{FCL-min}} \leq z_{\text{FCL-N}} \leq z_{\text{FCL-max}}$$ \quad (12)

where $N_{\text{FCL}}$ is the number of the R-FCLs; $m$ is the cost coefficient related to $N_{\text{FCL}}$; $z_{\text{FCL-N}}$ is the current-limiting impedance of the $N_{\text{th}}$ R-FCL; $p$ is the cost coefficient related to the total impedance of the R-FCLs; $F_c$ represents the penalty function used in the capital cost minimization; and this penalty function is determined by the fault current features. If the R-FCLs make the fault currents in all nodes lower than the permissible limit ($I_{i-\text{FCL}} < I_{\text{max}}$), $F_c = 0$ is achieved. Otherwise, the penalty function will be rewritten as $F_c = c \sum_{i=1}^{n} (I_{i-\text{FCL}} - I_{\text{max}})$, and $c$ is the penalty coefficient.

3.2 | Current-limiting performance of the R-FCLs

The second objective function $F_2$ is to minimize the fault currents, and $F_2$ is formulated as follows:

$$F_2 = \frac{\sum_{i=1}^{n} I_{i-\text{FCL}}}{\sum_{i=1}^{n} I_{i-\text{without-FCL}}} + F_d$$ \quad (13)

$$F_d = \frac{d \sum_{i=1}^{n} \max\{I_{i-\text{FCL}} - I_{\text{max}}, 0\}}{\sum_{i=1}^{n} I_{i-\text{without-FCL}}}$$ \quad (14)

where $F_d$ is the penalty function used in the fault current minimization. Similarly, it is desired that the fault currents in all nodes are completely suppressed, so as to obtain $F_d = 0$. If the fault currents in some nodes cannot meet the requirements, an adaptive penalty function will be introduced, and the amount of $F_d$ will be determined by the current differences rather than a constant setting value.

3.3 | Multiobjective function and Pareto optimal solutions

From the above, the Equation (15) signifies the multiobjective function and constraints concerning the optimal allocation of the R-FCLs:

$$F = \begin{cases} \min (F_1) \\ \min (F_2) \end{cases}$$

s.t.

$$I_{i-\text{FCL}} < I_{\text{max}}$$

$$N_{\text{min}} \leq N_{\text{FCL}} \leq N_{\text{max}}$$

$$z_{\text{FCL-min}} \leq z_{\text{FCL-N}} \leq z_{\text{FCL-max}}$$

Based on the Equation (15), it is able to simultaneously optimize the number, placement, and size of the R-FCLs. Note that, the objective functions of $F_1$ and $F_2$ are essentially conflicting to each other, and it is suitable for adopting a nondominated sorting principle to obtain the Pareto front.\(^{37-39}\) The purpose of the Pareto optimization is to abandon the dominated solutions and reserve the nondominated solutions, and it is expected to realize the Pareto predominance equilibrium between the conflicting objectives. For the Pareto dominance technique, it does not use weightage factor for converting multiobjective to single-objective optimization, and all solutions in the nondominated Pareto front are regarded as the optimization results.\(^{40,41}\)

To handle the Pareto optimization problem, adopting a favorable intelligent algorithm is very crucial, and it should own the following features: (a) reasonably generating initial solutions in the space; (b) efficiently implementing the iterative computation with reduced time; and (c) scientifically abandoning the dominated solutions and reserving the nondominated solutions. In this study, our research group designs an improved multiobjective particle swarm optimization (MOPSO) algorithm and a multiobjective artificial
bee colony (MOABC) algorithm to solve the studied problem, and a detailed description of them is provided in the next section.

4 | MULTIOBJECTIVE INTELLIGENT ALGORITHMS AND OPTIMIZATION PROCEDURE

4.1 | Multiobjective particle swarm optimization (MOPSO)

MOPSO is a multiobjective version of PSO, which is a heuristic optimization technique modeling the features of swarms and using particles to represent the potential solutions. In PSO, each particle flies through the search space with a random speed and updates its position to obtain the best solution. In MOPSO, there may be no single best solution to find out. Hence, particles should take into consideration the nondominated solutions (pbest), one of which the swarm may acquire (gbest) so far in the event of updating the position. The modeling equations of particles velocity and position can be expressed as:

\[ v_i(t+1) = w \cdot v_i(t) + c_1 \cdot r_1 \cdot [p_{best_i} - x_i(t)] + c_2 \cdot r_2 \cdot [gbest_i - x_i(t)] \]  

\[ x_i(t+1) = x_i(t) + v_i(t+1) \]  

where \( v_i(t) \) indicates the velocity of the \( i \)th particle at the iteration \( t \); \( w \) is the inertia weighting coefficient; \( c_1 \) and \( c_2 \) are the weighted constants, respectively; \( r_1 \) and \( r_2 \) are two random numbers.
numbers with the range of $[0,1]$; and $x_i(t)$ denotes the position of the $i$th particle at the iteration $t$.

To enhance the capability of MOPSO on jumping out the local optima, this study introduces a position mutation scheme to implement an improvement, and it is also beneficial for the algorithm to quickly converge to the true Pareto front. The philosophy of the suggested scheme is to mutate the position of particles based on the mutation rate and the number of iterations. All particles in the space will be classified into three parts, where are remarked as part-I, part-II, and part-III, respectively. For the particles of part-I, there is no adoption of mutation operation, and they will retain the original moving trends. Concerning the particles of part-II, a constant mutation rate is introduced to disturb them for randomly generating new particles, which own better global search ability. Regarding the

**FIGURE 6** Overall process of the optimization procedure

**FIGURE 7** Schematic of the modified IEEE 33-node distribution system with centralized access of DGs
particles of part-III, a changeable mutation rate subject to the number of iterations is adopted, as formulated in:

\[ M_p = \left(1 - \frac{t}{\text{ger}}\right)^{hD} \]  \hspace{1cm} (18)

where \( M_p \) denotes the mutation rate; \( \text{ger} \) is the maximum number of iterations; \( h \) is the attenuation constant; and \( D \) indicates the dimension of optimization variables. Based on the Equation (18), it enables to generate a large number of the mutated particles at the initial stage of iterative computation.

Along with the increase in the number of iterations, the mutated particles will be reduced, and especially, there will be a considerable decrease at the end of the iterative computation. The reason of introducing a constant mutation rate as well as a changeable mutation rate is to keep the amount of the mutated particles during the whole iterative computation, and it can more efficiently form the true Pareto front and be away from the local optima. As shown in Figure 4, it indicates the flowchart of the improved MOPSO algorithm for Pareto optimization.

### Multiobjective artificial bee colony (MOABC) algorithm

MOABC is designed based on ABC which models the characteristics of real bees in searching foods and sharing information to other bees. This algorithm is easy to realize and owns little control parameters.\(^{44}\) In the ABC algorithm, each employed bee searches a new food source \( q_i \) near the current source \( y_i \), and the equation is modeled as follows:

\[ q_{ij} = y_{ij} + \phi_{ij} (y_{ij} - y_{kj}) \] \hspace{1cm} (19)

where the subset of variable \( k \) is denoted as \( k \in \{1,2,\ldots,SN\} \), and \( SN \) expresses the amount of the employed bees; the subset of variable \( j \) is signified as \( j \in \{1,2,\ldots,D\} \), and \( D \) is the dimension of optimization variables; the relation between \( k \) and \( j \) is \( k \neq j \); and \( \phi \) is a random number with the range of \([−1, 1]\).\(^{45}\)

Then, each onlooker bee selects a food source in light of a probability \( P_i \) as formulated in:

\[ P_i = \frac{\text{fit}(y_i)}{\sum_{i=1}^{SN} \text{fit}(y_i)} \] \hspace{1cm} (20)

where \( \text{fit}(y_i) \) is a fitness function to represent the nectar amount of a food source.

The fitness function of the MOABC is as follows:

\[ \text{fit}(y_i) = \frac{\text{DomNum}(y_i)}{SN} \] \hspace{1cm} (21)

where \( \text{DomNum} \) denotes the number of the dominated solutions at the source \( y_i \).

If a food source is not able to be enhanced after predetermined cycles, it should be removed from the population. The employed bee in that food source will become scout, so as to search a new random food source. These steps are repeated by iterative computation until the stopping criterion is satisfied. As shown in Figure 5, it indicates the flowchart of the MOABC algorithm for Pareto optimization.
### 4.3 Optimization procedure

The overall process of the optimization procedure is shown in Figure 6, and the detailed steps are given below.

1. Read the system parameters of the ADNs (impedance matrix and main power source) and acquire the information on the position and capacity of DGs.
2. Calculate the three-phase fault currents in all nodes of the ADNs.
3. Use the sensitivity analysis to rank the candidate locations.
4. Set the installation number of the R-FCLs and put them into the candidate branches of the ADNs.
5. Implement the improved MOPSO and MOABC algorithms on the created multiobjective function.
6. Terminate the iterative computation when the stopping criterion is met. Else adjust the installation number of the R-FCLs and continue the optimization calculation.

7. Give the Pareto front to represent the optimal allocation of the R-FCLs.

## 5 PERFORMANCE VERIFICATION OF THE PROPOSED APPROACH

This section is devoted to the performance assessment of the proposed approach in the modified IEEE 33-node and 69-node distribution systems, where both centralized and dispersed access of DGs are considered.

### 5.1 IEEE 33-node distribution system with centralized access of DGs

Figure 7 shows the schematic of the modified IEEE 33-node distribution system, where the centralized access of DGs (mainly for synchronous DGs with considerable fault current contributions) is applied. The rated voltage of the system is 12.66 kV, and the total load is 3715 kW + j2300 kVar. The capacity of the IIDG is same as that of the synchronous DG, and it is uniformly set as 500 kVA. Three IIDGs (marked as DG2, DG3, and DG6) are connected to nodes 11, 18, and 28, respectively, and three synchronous DGs (marked as DG1, DG4, and DG5) are connected to nodes 6, 20, and 23, respectively.

For the demonstrated system, the permissible current limit under the three-phase fault is 17 kA. By performing the short-circuit calculation for all nodes, it is found that the fault currents in six nodes exceed the permitted limit.

As shown in Table 1, it gives the fault currents and candidate branches to install the R-FCLs based on the sensitivity analysis. There are eight candidate branches to install the R-FCLs, that is, the branches 1-2, 2-3, 2-19, 3-4, 3-23, 4-5, 5-6, and 19-20, respectively. Further, the number of the R-FCLs is regulated within the range of [1, 4], and the
optimization calculation is performed using the improved MOPSO algorithm.

Figure 8 shows the Pareto front features of the R-FCLs. It is obtained that only installing one R-FCL cannot satisfy the fault current constraints, and introducing multiple R-FCLs is needed. For the number of the R-FCLs fixed, a saturation phenomenon can be noticed, and increasing the impedance (cost) of the R-FCLs can no longer improve the current-limiting performance. From Figure 8, we select three cases (marked as Case I, Case II, and Case III), which represent three optimized solutions with different numbers and current-limiting behaviors of the R-FCLs, and detailed optimization data are listed in Table 2.

Figure 9 signifies the fault current with the optimized allocation of the R-FCLs. Due to the proposed approach, the fault currents in all nodes are decreased below the allowable limit. Taking Case III for the performance analysis, it shows that installing four R-FCLs can obtain very considerable limiting functions at nodes 2 and 3, and the current-limiting ratios are respectively 90.6% and 89.7%. For the fault currents in nodes 1, 6, 20, and 23, some moderate functions with the current-limiting ratios of [7.1%, 29.8%] are obtained to meet the criterion.

Figure 10 shows the comparison of the improved MOPSO and MOABC algorithms in the studied optimization problem, where four R-FCLs are applied. It is seen that the Pareto fronts obtained by the two algorithms are similar to each other, but the convergence speed of the improved MOPSO is much better than that of the MOABC. The improved MOPSO acquires the desirable nondominated solutions after 150 iterations. In comparison, the MOABC should perform 280 iterations.

5.2 | IEEE 33-node distribution system with dispersed access of DGs

Figure 11 shows the schematic of the modified IEEE 33-node distribution system with dispersed access of DGs. From the figure, three IIDGs (marked as DG1, DG3, and DG6) are connected to nodes 8, 19, and 32, respectively, and three synchronous DGs (marked as DG2, DG4, and DG5) are connected to nodes 15, 24, and 27, respectively. The capacity of each DG is still set as 500 kVA. According to the short-circuit calculation, the fault currents in nodes 1, 2, 24, and 27 are 18.0239 kA, 17.1508 kA, 17.3438 kA, and 17.1323 kA, respectively. Hence, as compared to the centralized access mode, the dispersed access of DGs may not only reduce the number of nodes where the fault currents exceed the permitted limit, but also lower the maximum fault current level.

Based on the sensitivity analysis, eight candidate branches are ranked to install the R-FCLs, that is, the branches 1-2, 2-3, 3-23, 4-5, 5-6, 6-26, 23-24, and 26-27, respectively.
Using the improved MOPSO, Figure 12 shows the Pareto front features of the R-FCLs in the IEEE 33-node distribution system with dispersed access of DGs. Here, installing one R-FCL is capable of meeting the fault current constraints, and the Pareto optimal solutions can be acquired. In a similar way, we choose four cases from Figure 12, and they are marked as Case I, Case II, Case III, and Case IV, respectively.

Table 3 indicates the optimization solutions of the selected four cases in the IEEE 33-node distribution system with dispersed access of DGs.

| Item | Installation number | Candidate placement | Limiting impedance | Objective function $F_1$ | Objective function $F_2$ |
|------|---------------------|---------------------|--------------------|--------------------------|--------------------------|
| Case I | 1 | 1-2 | 3.2164 $\Omega$ | 1.4825 | 0.8462 |
| Case II | 2 | 1-2 | 2.6064 $\Omega$ | 2.7155 | 0.7549 |
| | | 26-27 | 2.1634 $\Omega$ | | |
| Case III | 3 | 1-2 | 5.9869 $\Omega$ | 5.4146 | 0.6307 |
| | | 23-24 | 5.0304 $\Omega$ | | |
| | | 26-27 | 5.0798 $\Omega$ | | |
| Case IV | 4 | 1-2 | 12.2155 $\Omega$ | 10.1612 | 0.5484 |
| | | 5-6 | 8.7304 $\Omega$ | | |
| | | 23-24 | 11.1509 $\Omega$ | | |
| | | 26-27 | 8.9781 $\Omega$ | | |

To inspect the efficacy of the sensitivity analysis in the studied optimization problem, Figures 14,15 show the impacts of the sensitivity analysis on the iterative computation and the Pareto front. From Figure 14, it is confirmed that the sensitivity analysis can visibly decrease the number of iterative computation, in particular, for that more R-FCLs are installed.

From Figure 15, the sensitivity analysis changes the Pareto front when optimizing four R-FCLs. Here, the intention of introducing the sensitivity analysis is to make the R-FCLs more effective for the critical nodes where the fault currents exceed the limit. Along with increasing the number of the R-FCLs, the current-limiting functions to the critical nodes may easily become saturated, but there is room for the noncritical nodes. Hence, if the sensitivity analysis is not adopted, a wider range of scanning the
candidate locations will be done. More computation time is needed, and it may contribute to getting a little bit better current-limiting functions to all nodes.

### 5.3 IEEE 69-node distribution system with dispersed access of DGs

To evaluate the proposed approach in more complex ADNs, the modified IEEE 69-node distribution system with dispersed access of DGs is built, and the schematic connection diagram is shown in Figure 16. In the system, the rated voltage is 12.66 kV, and the total load is 4562 kW + j2694 kVar. Four IIDGs (marked as DG1, DG5, DG6, and DG7) are jointed to nodes 5, 48, 57, and 59, respectively, and four synchronous DGs (marked as DG2, DG3, DG4, and DG8) are accessed to nodes 15, 24, 33, and 65, respectively. The capacity of each DG is uniformly set as 500 kVA. From the short-circuit calculation, there are eleven nodes where the fault currents exceed the limit, and the sensitivity analysis is used for ranking twenty candidate branches to accommodate the R-FCLs. Detailed fault currents and candidate locations are listed in Table 4.

Figure 17 shows the Pareto front features of optimizing the R-FCLs in this complex system. For that, the number of the R-FCLs is changeable, and the obtained current-limiting zone will be clearly different. To carry out a comparative analysis, three cases (Case I, Case II, and Case III) are selected, and they represent three optimized solutions with different numbers and current-limiting behaviors of the
R-FCLs. Detailed optimization results and fault current data are indicated in Table 5 and Figure 18.

At the end, we compare the improved MOPSO and MOABC algorithms in the IEEE 69-node system accommodating four R-FCLs. Figure 19 shows the influence of the two algorithms on the Pareto front and number of iterative computation. Herein, three different optimal solutions are selected, and Table 6 indicates the performance data. The comparison of solution I and solution II is to prove that when the cost of the R-FCLs is fixed, the improved MOPSO can optimize the R-FCLs to achieve a stronger fault current suppression than the MOABC. By comparing solution II and solution III, it is to demonstrate that the improved MOPSO can more economically utilize the R-FCLs than the MOABC to realize the same fault current limitation. Owing to the improved MOPSO, not merely a better Pareto front is achieved, but also the whole optimization process is accelerated. It implies that, for a large-scale complex system with many candidate locations to accommodate the R-FCLs, the improved MOPSO can more efficiently optimize the R-FCLs to achieve the Pareto predominance equilibrium, and it obtains better objective functions of minimizing the cost of R-FCLs and the fault currents of the ADNs simultaneously than the MOABC.

6 | TECHNICAL DISCUSSIONS

In this section, technical discussions about the implications of the R-FCLs on the circuit breakers and protective relays are conducted. Additionally, regarding the application of sensitivity analysis methods in the optimization technique, a brief discussion is implemented.

| Node number | Fault current/kA | Ranking of candidate branches based on the sensitivity analysis |
|-------------|------------------|---------------------------------------------------------------|
| 1           | 20.9377          | 2-3 (0.1294); 1-2 (0.1294); 3-28 (0.0269); 28-29 (0.0268)   |
| 2           | 20.9822          | 1-2 (0.5177); 2-3 (0.1301); 3-28 (0.0270); 28-29 (0.0270) |
| 3           | 21.025           | 1-2 (0.5128); 2-3 (0.5128); 3-28 (0.0271); 28-29 (0.0271) |
| 4           | 20.8118          | 3-4 (0.9233); 2-3 (0.5123); 1-2 (0.5123); 3-28 (0.0271)    |
| 5           | 19.0941          | 4-5 (0.9156); 3-4 (0.9124); 2-3 (0.5063); 1-2 (0.5063)     |
| 15          | 17.6522          | 15-16 (0.0331); 16-17 (0.0331); 17-18 (0.0330); 19-20 (0.0330) |
| 28          | 20.5304          | 3-28 (0.7632); 2-3 (0.5081); 1-2 (0.5081); 28-29 (0.0287)  |
| 33          | 17.2703          | 31-32 (0.0403); 32-33 (0.0403); 29-30 (0.0403); 30-31 (0.0403) |
| 36          | 19.132           | 4-36 (0.9964); 3-4 (0.9232); 2-3 (0.5123); 1-2 (0.5123)   |
| 59          | 20.5392          | 3-59 (0.7325); 1-2 (0.5079); 2-3 (0.5079); 3-28 (0.0269)  |
| 65          | 17.8304          | 64-65 (0.0303); 63-64 (0.0303); 62-63 (0.0303); 61-62 (0.0303) |

TABLE 4 Fault currents and candidate branches to install the R-FCLs in the IEEE 69-node distribution system with dispersed access of DGs
6.1 Influence of the R-FCLs on traditional protective devices

Through the optimal allocation of the R-FCLs, the fault currents in all nodes are decreased within the allowable levels, and it is to ensure that existing circuit breakers have adequate capacity margins to meet the operating conditions. Furthermore, using the R-FCLs has great potential to lower the rate of rise of recovery voltage (RRRV) across the circuit breakers, and it is helpful to facilitate the arc extinction and avoid the arc re-ignition.48,49 In light of these two contributions, the implications of the R-FCLs can alleviate the transient burden of the circuit breakers to realize a reliable interruption and isolation of short-circuit faults.

In the power distribution systems, the primary and backup overcurrent relays are commonly adopted, and their operating time features can be modeled as:

\[
t_{\text{primary}} = \left( \frac{A}{I_{f,\text{primary}}/I_{\text{pick-up,primary}}} \right)^C - 1 + B \times \text{TDS}_{\text{primary}} \tag{22}
\]

\[
t_{\text{backup}} = \left( \frac{A}{I_{f,\text{backup}}/I_{\text{pick-up,backup}}} \right)^C - 1 + B \times \text{TDS}_{\text{backup}} \tag{23}
\]

where \(I_{\text{pick-up}}\) denotes the pick-up current of the relay; TDS indicates the time dial setting; \(A, B,\) and \(C\) represent the relay characteristic constants.

To make the primary and backup relays meet the requirement of selectivity (a specified operation sequence), the coordination time CTI is defined as follows:

\[
\text{CTI} = t_{\text{backup}} - t_{\text{primary}} \tag{24}
\]

where the typical range of CTI is [0.2 s, 0.5 s].

In a way, higher fault currents by the integration of DGs may considerably reduce CTI and cause that the protective relays lose the coordination.51,52 Due to the R-FCLs, the fault currents are appreciatively suppressed, and the desired coordination of the overcurrent relays in the ADNs can be potentially restored. As one improvement of our study, the joint optimization of the protective relays and the R-FCLs will be done in the near future. It is aimed to realize the optimal coordination and utilize the performance advantages of the R-FCLs in the ADNs more fully.

6.2 Application of sensitivity analysis methods in the optimization technique

This study introduces the impedance sensitivity analysis for ranking the candidate locations of the R-FCLs. By analyzing the sensitivity of the original impedance matrix to the current-limiting impedances, it enables to make the R-FCLs

| Item  | Installation number | Candidate placement | Limiting impedance | Objective function \(F_1\) | Objective function \(F_2\) |
|-------|---------------------|---------------------|--------------------|-----------------------------|-----------------------------|
| Case I| 2                   | 1-2                 | 4.4462 Ω           | 2.9276                      | 0.7093                      |
|       |                     | 15-16               | 1.7380 Ω           |                             |                             |
| Case II| 3                   | 1-2                 | 3.7729 Ω           | 4.4153                      | 0.6215                      |
|       |                     | 3-4                 | 3.0278 Ω           |                             |                             |
|       |                     | 15-16               | 2.6346 Ω           |                             |                             |
| Case III| 4                  | 1-2                 | 11.9199 Ω          | 9.5446                      | 0.4894                      |
|       |                     | 15-16               | 6.3953 Ω           |                             |                             |
|       |                     | 32-33               | 7.9548 Ω           |                             |                             |
|       |                     | 64-65               | 10.6942 Ω          |                             |                             |

**TABLE 5** Optimization solutions of the selected three cases in the IEEE 69-node distribution system with dispersed access of DGs

**FIGURE 18** Fault current with the optimized allocation of the R-FCLs in the IEEE 69-node distribution system with dispersed access of DGs
more effective to affect the critical nodes where the fault currents exceed the permissible levels. From the numerical results, using the sensitivity analysis can visibly reduce the number of iterations, especially for the ADNs accommodating more R-FCLs.

Note that, this study does not consider the node voltage change caused by the power fluctuations of DGs. In a sense, a larger voltage change will result in an obvious current fluctuation, and there might be a probability of the R-FCLs being improperly activated. To address this problem, it should be a feasible option to introduce an efficient method of voltage sensitivity analysis, which enables to achieve the straightforward analytical computation of the voltage change caused.

**FIGURE 19** Comparison of the improved MOPSO and MOABC algorithms in the IEEE 69-node distribution system. (A) Pareto front and (B) number of iterative computation.

**TABLE 6** Comparison of the improved MOPSO and MOABC in optimizing four R-FCLs in the IEEE 69-node distribution system with dispersed access of DGs.
by the behavior change of generation and load choices. The analytical results of the voltage change can be used to identify the branches that are not suitable for accommodating the R-FCLs. The voltage sensitivity analysis of the ADNs and its effects on the optimal allocation of the R-FCLs will be investigated in our follow-on study.

7 | CONCLUSIONS

This paper puts forward a novel methodology for Pareto optimal allocation of R-FCLs in the active distribution networks with IIDGs and synchronous DGs. Considering the centralized and dispersed access of multiple DGs, the proposed approach is validated in the modified IEEE 33-node and 69-node distribution systems. From the numerical results, the major conclusions are drawn as follows.

1. The formulated objectives are met simultaneously. The fault currents in all nodes are limited to the permissible levels using the least capital cost of the R-FCLs, no matter how the scale of testing systems and the access mode of DGs are changing.
2. The improved MOPSO outperforms the MOABC to solve the studied optimization problem. Especially for the large-scale complex system, the improved MOPSO can find a better Pareto front and reduce the number of iterative computation.

In consequence, the feasibility and superiority of the proposed approach are well demonstrated. Note that, there are still potential improvements to be done. In the near further, our research group plans to consider the operating time features of overcurrent relays in the constrained multiobjective function, and the joint optimization of the protective relays and the R-FCLs in the ADNs will be explored. Besides, the voltage sensitivity analysis will be introduced, and its impacts on optimizing the R-FCLs will be clarified. The research results will be presented in other articles.

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NOMENCLATURE

ABBREVIATIONS

DG, Distributed generator; GA, Genetic algorithm; LP, Linear programming; ADN, Active distribution network; COA, Cuckoo optimization algorithm; CTI, Coordination time; FCL, Fault current limiter; PSO, Particle swarm optimization; IIDG, Inverter-interfaced distributed generator; R-FCL, Resistive-type fault current limiter; RRRV, Rate of rise of recovery voltage; MOABC, Multiobjective artificial bee colony; MOPSO, Multiobjective particle swarm optimization.

SYMBOLS

\( E \) Electromotive force [V]
\( U \) Voltage [V]
\( t \) Time [s]
\( z \) Impedance [Ω]
\( F \) Function [–]
\( x \) Position of the particle [–]
\( M \) Mutation rate [–]
\( P \) Probability [–]
\( N \) Number [–]
\( D \) Dimension [–]
\( d \) Penalty coefficient for the fault current reduction [–]
\( I \) Current [A]
\( R \) Resistance [Ω]
\( X \) Reactance [Ω]
\( Z \) Impedance matrix [Ω]
\( \eta \) Sensitivity [–]
\( v \) Velocity of the particle [–]
\( w \) Inertia weighting coefficient [–]
\( SN \) Amount of the employed bee [–]
\( c \) Penalty coefficient for the R-FCL cost [–]

SUBSCRIPTS

\( s \) Synchronous
\( n \) Node
\( qs \) Quench starting
\( sr \) Secondary-stage recovery
\( k \) Fault site
\( ns \) Normal state
\( fr \) First-stage recovery
\( cr \) Completed recovery
\( max \) Maximum value

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