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Optimal coordination of overcurrent relays in distribution systems with distributed generators based on differential evolution algorithm

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SUMMARY

Distributed generators (DGs) are defined as generators that are connected to a distribution network. The direction of the power flow and short-circuit current in a network could be changed compared with one without DGs. The conventional protective relay scheme does not meet the requirement in this emerging situation. As the number and capacity of DGs in the distribution network increase, the problem of coordinating protective relays becomes more challenging. Given this background, the protective relay coordination problem in distribution systems is investigated, with directional overcurrent relays taken as an example, and formulated as a mixed integer nonlinear programming problem. A mathematical model describing this problem is first developed, and the well-developed differential evolution algorithm is then used to solve it. Finally, a sample system is used to demonstrate the feasibility and efficiency of the developed method. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: distributed generation; distribution system; coordination of protective relays; directional relay; differential evolution algorithm

1. INTRODUCTION

A distributed generator (DG) is usually defined as a small-scale generator with a capacity between 3 kW and 100 MW [1] and is normally connected to a distribution network. Distributed generation is helpful for improving the distribution system's operation and power supply, especially in rural and remote areas [2]. Specifically, the advantages of DG can be summarized as follows: enhancing reliability, reducing network losses, improving power quality, postponing network expansion, improving the environment by reducing carbon dioxide and nitrogen oxide emissions, and providing peak load service [3–6]. In recent years, distributed generation has developed rapidly as a result of the restructuring of the power industry and the environmental concerns of people around the globe [7].

However, the rapid increase in the number and capacity of DGs has also brought some problems to power system operation and control [7–12]. Whether the abovementioned advantages of DGs can be achieved depends heavily on the proper resolution of these problems; one important issue is the coordination of protective devices [13,14]. Traditionally, the distribution system operates in a radial configuration, and its power flow and short-circuit current are flowing in one direction only. The inclusion of DGs in a distribution network could change the direction of the power flow and the short-circuit current. If conventional overcurrent protection/overcurrent relay systems are still used, malfunctions in protection may happen because of the change in the direction of the current. The conventional protective relay scheme does not meet the requirement in this emerging situation. As the number and capacity of DGs increase in the distribution system, the issues concerned, namely, the protective relay system design and coordination, will become increasingly challenging [15]. It is expected that replacing protective devices will incur large amounts of investment and may not be cost-effective. Instead, the

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problem may be resolved by appropriately coordinating the relay settings of the existing protective relays to achieve a cost-efficient outcome, at least for low levels of penetration of DGs.

Protective relay coordination refers to the ability to select appropriate relay setting values so that they can meet the basic requirements for protective relays, namely, selectivity, speed, sensitivity, and reliability [16], under different kinds of faults. An appropriately coordinated protection system can isolate faults quickly and maintain the operation of the remaining healthy part of the system [17]. Directional overcurrent relays are widely used in distribution systems; hence, it is very important to investigate the coordination problem when using these protective relays [18]. Some research work has been done in this area but, in most of the existing methods, linear or nonlinear programming approaches are used for this purpose [16]. Only continuous variables can be handled in these approaches, and thus the results obtained have to be rounded off to the nearest discrete value. Hence, the optimality of the coordination results cannot be maintained.

Given this background, the optimal coordination problem of overcurrent relays is revisited and formulated as a mixed integer nonlinear programming (MINLP) problem in this work. In the formulation, the pickup current setting is a discrete variable, whereas the time setting multiplier is continuous. As each protective relay in the distribution system must be properly coordinated with the adjacent relays, the coordination of the protection system could be very complicated. In this work, the well-established differential evolution (DE) algorithm [19] was used to solve this problem. The abovementioned problem of rounding the optimal solution of continuous variables in existing methods can be avoided in this DE-based method. First, the mathematical model of the directional overcurrent relay coordination problem is formulated, with the objective of minimizing the operating time of protective relays. Then, the DE algorithm is briefly introduced. Finally, a numerical example is presented to demonstrate the proposed approach.

2. THE MATHEMATICAL MODEL

2.1. Primary/backup coordinating pairs

The primary/backup coordinating pairs of overcurrent relays can be illustrated by a simple example shown in Figure 1. If a three-phase short-circuit fault occurs on bus **C**, the short-circuited current will flow from line AB to line BC. In this case, relay 1 is the primary protection and relay 2 the backup protection. These two protection units form a coordinating pair and could be described as (R_2, R_1). For a general case, the set of coordinating pairs could be defined as $R_{PB} = \{(R_B, R_P)\}$, where R_P is the primary protection and R_B the backup protection. A coordination time interval should be imposed between a primary and a backup coordinating pair so as to maintain the selectivity and coordination. For this purpose, all the primary/backup coordinating pairs must first be found.

2.2. A uniform model for optimal coordination of relays

To facilitate the presentation, a general nonlinear programming model is first introduced:

$$\text{Min}: \ f(x) \tag{1}$$

$$\text{s.t.}: \ g(x) = 0 \tag{2}$$

$$h_{\min} \leq h(x) \leq h_{\max} \tag{3}$$

where $f(x)$ is the objective function, x is the variable to be determined, $g(x) = [g_1(x), \cdots, g_m(x)]^T$, m is the number of equality constraints, $h(x) = [h_1(x), \cdots, h_r(x)]^T$, r is the number of inequality constraints, $h_{\max}$

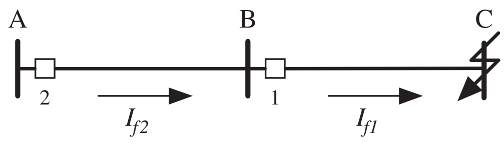

Figure 1. An illustration of a relay coordinating pair.

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and h_{min} are the vectors of the upper and lower bounds for the inequality constraints, respectively, $h_{min} = [h_{1\,min}, \cdots, h_{r\,min}]^T$, and $h_{max} = [h_{1\,max}, \cdots, h_{r\,max}]^T$.

As for the optimal coordination problem of protective relays in distribution systems, the objective is actually to minimize the operating time of relays under the constraints of selectivity, sensitivity, reliability, and relay characteristic curves. This problem could be formulated as an optimization model:

$$\min_{x \in X} \quad f(x,p) \tag{4}$$

$$\text{s.t.: } t = g(x) \text{(relay characteristic function)} \tag{5}$$

$$h(x) \leq 0 \quad \text{(coordination constraint)} \tag{6}$$

$$x_{\min} \leq x \leq x_{\max} \quad \text{(relay settings constraint)} \tag{7}$$

$$t_{\min} \leq t \leq t_{\max} \quad \text{(operating time constraint)} \tag{8}$$

where $f(x)$ is the objective function; x is the variable to be determined, that is, relay settings parameters; X is the set of available settings; p is a set of perturbations or fault conditions in a specified zone; and t is the operating time of a relay.

In the previously mentioned optimization model, Equation (6) represents the selectivity constraint used to maintain the selectivity between the primary protection and the backup protection. Equation (7) represents the sensitivity constraint used to make sure that a relay can operate when a fault occurs within its protection range by appropriately setting the relay parameters. Equation (8) represents the reliability constraint used to guarantee that when a fault occurs within a relay's protection range, the relay must operate within the bounds of the operating time. In summary, the optimal coordination problem of protective relays is that of minimizing the operating time of relays while respecting these constraints.

2.3. *The optimization model of overcurrent relays*

The minimization of the total operating time of a protective relay system under different fault zones is taken as the objective of the optimal coordination problem of protective relays. Specific to directional overcurrent relays, the optimal coordination problem determines two parameters, that is, the pickup current setting and the time setting multiplier. The objective function for the optimal coordination problem of directional overcurrent relays can be described as

$$\min J = \sum_{i=1}^{N_P} w_i t_{iL} \tag{9}$$

where N_P is the number of primary and backup relays, w_i is a coefficient representing the probability of the occurrence of a fault and could be set to 1 for all possible faults if reliable data are not available, and t_{iL} is the operating time of the ith relay when a fault occurs in zone L.

The smaller the objective function, the better the coordination of the protective relays. In the case of the optimal solution, the total operating time of the protective relays in the protection system studied is minimized under all specified faults. In this way, faults can be cleared quickly if they are included in the specified kinds of faults.

In minimizing the objective function, some constraints must be taken into account, such as the relay current/time characteristics, the constraints on the time setting multiplier and the operating time, the pickup current setting, and the coordination time of relays. These constraints are detailed in the following paragraphs.

(1) The relay current/time characteristics

The current/time characteristic curves of an overcurrent protection consist of two types, that is, the definite time and inverse time curves.

(a) The definite time characteristic relay

The operating time of a definite time characteristic relay is independent of the short-circuited current, and can be defined as

$$t_i = \mathrm{C}_{\text{const}} \tag{10}$$

where t_i is the operating time of relay R_i and C_{const} is a constant.

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If the definite time characteristic relays are used for the optimal coordination of overcurrent relays in distribution systems, the objective function is Equation (9) and the constraints are Equations (13) and (14). It is obvious that the optimality analysis is not demanded in a radial distribution system if the fault current is larger than the pickup current because the operating time of all relays could be obtained by the backward process on the basis of the coordination time interval, as long as the operating time of the relay at the end of the feeder concerned is known. Hence, the definite time characteristic relay is usually not considered in the optimal coordination problem of overcurrent relays in distribution systems.

(b) The inverse time characteristic relay

The operating time of the inverse time characteristic relay is dependent on the short-circuited current. The larger the current is, the shorter the operating time will be. To some extent, this characteristic is adaptive. The current/time characteristic of a directional overcurrent relay under the Institute for Electrical and Electronic Engineers (IEEE) standard C37.112-1996 and IEC 255–3 can be expressed as

$$t_{iL} = \frac{T_{\mathrm{M}i} \times \lambda}{\left(\frac{I_{iL}}{I_{\mathrm{P}i}}\right)^{\gamma} - 1} \tag{11}$$

where $T_{\mathrm{M}i}$ is the time setting multiplier, I_{iL} is the short-circuited current passing through the relay when a fault occurs in zone L, $I_{\mathrm{P}i}$ is the pickup current setting of the ith relay, and λ and γ are constants.

(2) Constraints on the time setting multiplier and the operating time

$$T_{\mathrm{M}i\,\min} \leq T_{\mathrm{M}i} \leq T_{\mathrm{M}i\,\max} \tag{12}$$

$$t_{i\,\min} \leq t_i \leq t_{i\,\max} \tag{13}$$

where $T_{\mathrm{M}i}$ is in the range of 0.01 to 1.

(3) Constraints on the pickup current setting

Because the pickup current setting of each overcurrent protective relay is discrete, a 0–1 variable y_{mi} is usually used in the existing methods [16], and the setting can be represented by the product of the pickup current–specified value and a binary variable. For example, if a relay has eight available relay pickup current–specified values, the pickup current setting can be formulated as

$$I_{\mathrm{P}1} = y_{11}I_{\mathrm{Pa}1} + y_{21}I_{\mathrm{Pa}2} + y_{31}I_{\mathrm{Pa}3} + y_{41}I_{\mathrm{Pa}4} + y_{51}I_{\mathrm{Pa}5} + y_{61}I_{\mathrm{Pa}6} + y_{71}I_{\mathrm{Pa}7} + y_{81}I_{\mathrm{Pa}8} \tag{14}$$

where $I_{\mathrm{Pa}1}, I_{\mathrm{Pa}2}, \ldots, I_{\mathrm{Pa}8}$ are the available relay pickup current–specified values. Equation (14) can be reformulated as

$$I_{\mathrm{P}i} = \sum_m y_{mi} I_{\mathrm{Pa}m} \forall i \qquad \text{where} i = 1, 2, \ldots, n \tag{15}$$

$$y_{mi} = \begin{cases} 1 & I_{\mathrm{P}i} = I_{\mathrm{Pa}m} \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

where n is the number of the relays, m is the number of the available relay pickup current–specified values, and $I_{\mathrm{Pa}m}$ is the mth relay pickup current setting for the ith relay.

To make sure that an available relay pickup current–specified value can be chosen for each relay, the following constraint has to be imposed on y_{mi},

$$\sum_m y_{mi} = 1 \qquad \forall i \quad \text{where} \quad i = 1, 2, \ldots, n \tag{17}$$

It can be seen from Equation (17) that if one of the binary variables for a relay is equal to 1, then all the others for the same relay will be 0.

However, the number of control variables is usually very large and the computational efficiency is low in the existing methods. Given this background, an alternative method is presented here in which integer variables are used rather than binary variables. Specifically, each value of an integer variable represents an available relay pickup current. In this way, each relay has only one integer variable, so the numbers of the control variables can be reduced significantly. On this basis, the well-developed DE [19] will be used to solve the problem.

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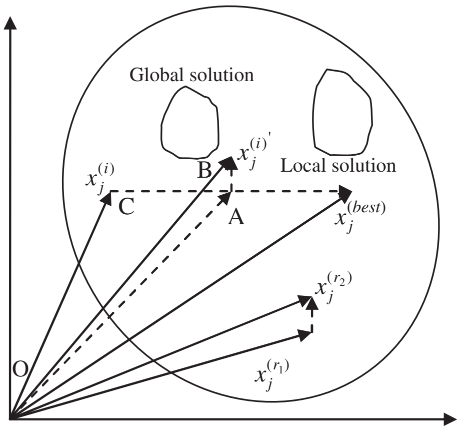

Figure 2. The reproduction mechanism of the DE algorithm.

In addition, the pickup current setting I_{pi} of each overcurrent relay must meet the following constraint:

$$I_{Pi\min} \leq I_{Pi} \leq I_{Pi\max} \tag{18}$$

From Equation (18), it can be observed that the pickup current setting for each relay is determined by two parameters, namely, the minimum fault current and the maximum load current [18]. The minimum pickup current is generally specified as being 1.5 to 2 times of the normal load current to maintain the secure operation of the power system concerned. The maximum pickup current is determined such that it is less than the fault current passing through the relay to activate the operation of the relay when a fault occurs [20].

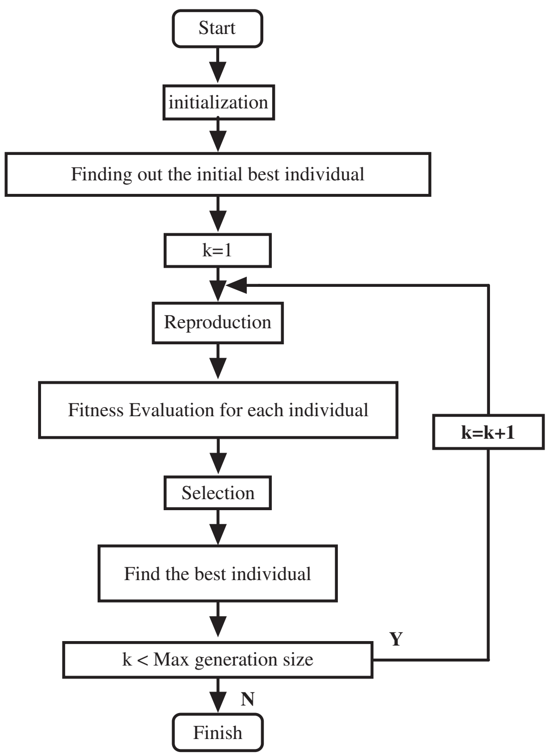

Figure 3. The flowchart of the DE algorithm.

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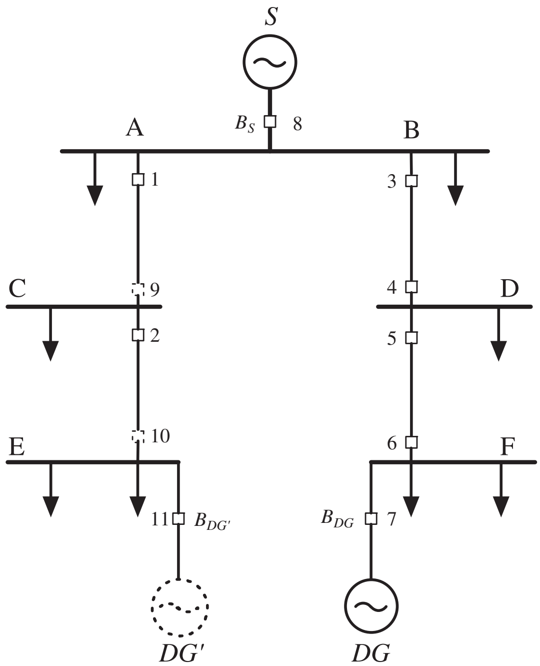

Figure 4. The sample distribution system.

(4) Constraints on the coordination time interval of protective relays

When a primary protective relay does not operate properly, a backup protective relay must operate to isolate the fault. The coordination time interval is the difference between the operating time of the backup relay and that of the primary protective relay. This is the minimum time interval that permits the backup relay to clear a fault in its operating zone. Equation (19) is a fundamental constraint for the optimal coordination problem of protective relays:

$$t_{bL} - t_{iL} \geq C_{\mathrm{TI}} \tag{19}$$

where t_{bL} is the operating time of the backup relay R_i when a fault occurs in zone L and C_{TI} is the coordination time interval, usually specified between 0.2 and 0.5 s [16].

In the previously mentioned mathematical model, both discrete and continuous variables are included, and the objective function is nonlinear. Hence, this is an MINLP problem. In this work, the well-established DE algorithm is used to solve this MINLP problem.

3. THE DE ALGORITHM

The DE algorithm was advanced by Rainer Storn and Kenneth Price in 1995 [19] and represents a simple and effective evolutionary algorithm. The DE algorithm is proven faster than other evolutionary algorithms such as evolution strategy [21]. In 1999, Jouni Lampinen and Ivan Zelinka extended the DE algorithm to solve optimization problems with mixed variables and constraints, which promoted the wider use of the DE algorithm [19].

Table I. Power supply parameters.

$\mathbf{S_s}$	100 MVA	$\mathbf{V_s}$	10.5 kV	$\mathbf{X_s}$	1.46 Ω
$\mathbf{S_{DG}}$	10 MVA	$\mathbf{V_{DG}}$	10.5 kV	$\mathbf{X_{DG}}$	0.42 Ω
$\mathbf{f_s}$		50 Hz			

DOI: 10.1002/ete

Table II. Feeder parameters.

Line	R(Ω)	L(H)
A–C	1.155	0.005
C–E	1.155	0.005
B–D	1.155	0.005
D–F	1.155	0.005

3.1. Initialization

An initial population of N (population size) candidate solutions or individuals is first randomly generated according to Equation (12) and is used as the parent population of the first generation, $\bar{X}(0) = \{X_1(0),\, X_2(0), \cdots, X_N(0)\}$. Here, $X_i(0) = \left\{x_1^{(i)}(0), x_2^{(i)}(0), \cdots, x_B^{(i)}(0)\right\}$, where $x_j^{(i)}(k)$ is the jth control variable of the ith individual in generation k, $k = 0$ refers to the initialization population, and B is the number of control variables:

$$x_j^{(i)}(k) = U\left(l_{\mathrm{b}j}, u_{\mathrm{b}j}\right) \tag{20}$$

where $U(l_{\mathrm{b}j}, u_{\mathrm{b}j})$ generates a uniform random value between $u_{\mathrm{b}j}$ and $l_{\mathrm{b}j}$ of the control variable j and $u_{\mathrm{b}j}$ and $l_{\mathrm{b}j}$ are the upper and lower bounds of control variables, respectively.

In the existing methods, the control variables of the optimal coordination model are usually $T_{\mathrm{M}i}$ and y_{mi}. As mentioned previously, to reduce the number of the control variables, an integer variable Z_i is introduced to replace the binary variable y_{mi}. In this way, the number of the control variables is equal to the number of relays.

3.2. Reproduction

An offspring population can be reproduced by perturbing the value of each control variable in each individual in the parent population. A DE algorithm with the best individual in each generation retained is used in this work [22]. It reproduces the offspring population of the kth generation according to

$$x_j^{(i)\prime}(k) = x_j^{(i)}(k) + F_{\mathrm{w}}\left(x_j^{(best)}(k) - x_j^{(i)}(k)\right) + V_{\mathrm{w}}\left(x_j^{(r_1)}(k) - x_j^{(r_2)}(k)\right) \tag{21}$$

where F_{w} and V_{w} are zoom coefficients and are uniformly distributed in [0,1] and $x_j^{(\mathrm{best})}$ is the jth control variable of the best individual. This reproduction mechanism is illustrated in Figure 2.

If $x_j^{(i)\prime}(k)$ is not in $[l_{\mathrm{b}}, u_{\mathrm{b}}]$, then a random value is produced in $[l_{\mathrm{b}}, u_{\mathrm{b}}]$ and rounded off if it is not an integer.

Table III. The placements of primary/backup protective relays.

No.	No. primary relays	No. backup relays
1	2	1
2	1	4
3	1	8
4	3	8
5	4	6
6	5	3
7	6	7

Table IV. Simulation results.

T_{Mi}	Result	I_{Pi}	Result (A)
T_{M1}	0.0196	I_{P1}	1100
T_{M2}	0.0195	I_{P2}	400
T_{M3}	0.0192	I_{P3}	1100
T_{M4}	0.0565	I_{P4}	100
T_{M5}	0.0120	I_{P5}	600
T_{M6}	0.0136	I_{P6}	1000
T_{M7}	0.0689	I_{P7}	800
T_{M8}	0.0782	I_{P8}	1000
Objective value(s)	4.8576		
Fitness value	0.2059		

3.3. *The evaluation of individuals*

A fitness function is defined for evaluating the fitness of each individual as

$$f(X_i(k)) = \frac{1 - F_v \times \sum_{i=1}^{h} C_i}{\sum t_{iL}} \tag{22}$$

where $f(\ )$ is the fitness function, F_v is a penalty coefficient, h is the number of constraints, and C is the penalty value and is equal to 1 when it meets the constraint and 0 otherwise.

3.4. *Selection*

The selection strategy in the DE algorithm is very easy and can be described as a "one-to-one" selection. An offspring individual $x^{(i)'}(k)$ is compared with its parent individual $x_j^{(i)}(k)$, and the better one wins. The winning individuals form the updated population of generation k, which will then be used as the parent population of the next generation:

$$X_i(k+1) = \begin{cases} x_j^{(i)'}(k), & \text{if } \ f\left(x_j^{(i)'}(k)\right) > f\left(x_j^{(i)}(k)\right) \\ & x_j^{(i)}(k)\text{otherwise} \end{cases} \tag{23}$$

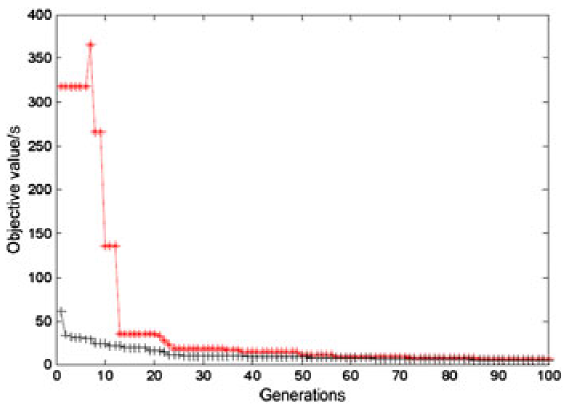

Figure 5. The objective value of the best individual and that of a given individual.

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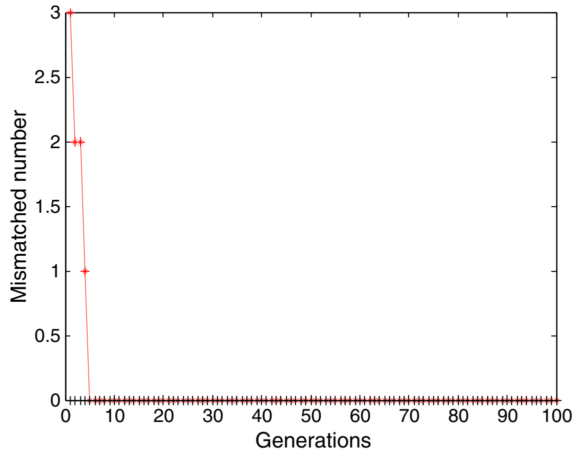

Figure 6. The mismatched number of protective relays in the best individual and a given individual.

3.5. Termination

The procedure will be terminated after a specified number of generations. The number of generations required to carry out the optimal coordination of protective relay settings depends on the population size and the number of initial relay settings. The flowchart of the DE algorithm is shown in Figure 3.

4. NUMERICAL EXAMPLES

In this work, the sample system by Zeienldin *et al*. [23] is slightly modified to demonstrate the developed approach, as shown in Figure 4. It is obvious that when DGs are removed, the original system is a radial network, whereas when DGs are added, the distribution system will become a looped one, and the power flow as well as short-circuited current will no longer flow in just one direction. Directional overcurrent relays could be used to protect the system. In this work, bus faults are used in case studies, but the developed mathematical model and algorithm could be applied to a variety of fault locations as well as different types of faults, as long as the constraints are included and respected. To keep the radial characteristic in the original distribution system and to solve the new problems mentioned, the case study is chosen with a DG installed at the end of feeder B. If another DG is installed at the end of feeder A, as shown with the broken line in Figure 4, three protective relays should be installed.

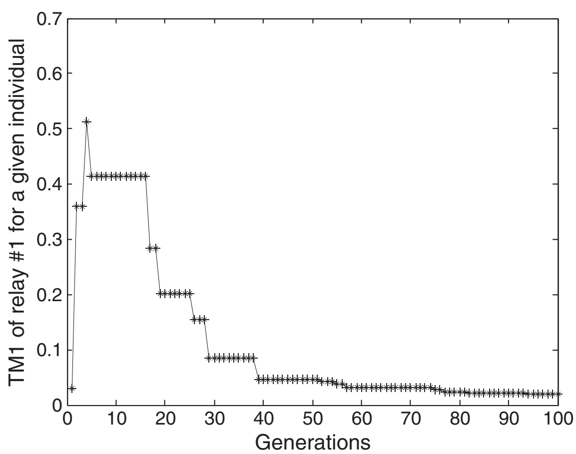

Figure 7. T_{M1} of relay 1 for a given individual.

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Table V. The coordination of the primary/backup protective relays.

No.	Coordination pairs	Coordination time (s)
1	2–1	0.4101
2	1–4	0.4049
3	1–8	0.4446
4	3–8	0.4070
5	4–6	0.4246
6	5–3	0.4170
7	6–7	0.4122

In this case, the current direction through each protective relay does not change when a fault takes place on a bus; the only change is the fault current amount. The mathematical model presented in this work can solve this situation.

The system shown in Figure 4 is a 10-kV distribution system with five buses and eight protective relays. A DG is installed at the end of feeder B. There are two circuit breakers; one at the public power supply point and the other at the distributed generation supply point. The DE algorithm is used to obtain the optimal time setting multiplier (T_M) and the pickup current setting value (I_P) of the directional overcurrent relay. The formulated model consists of 16 variables with eight discrete variables and eight continuous variables by using the proposed method; however, there will be 72 variables with eight discrete variables and 64 continuous variables if the existing method is used. It should be pointed out that the proposed method can be applied to larger and more complicated distribution systems with multiple DGs.

The original data of the sample system are shown in Tables 1–3, which show the power supply parameters, the feeder parameters, and the placements of primary/backup protective relays, respectively.

Many simulation tests have been carried out. The test results with the following specified parameters are listed in Table 4: the initial population size was $N=300$, and the maximum permitted number of generations was 100. To better understand the computational procedure of the DE algorithm, some simulation results are shown in Figures 5–7. The optimal objective value and the objective value of a given individual in each generation are shown in Figure 5, the mismatched number of protective relays in the best individual and a given individual are shown in Figure 6, and the T_{M1} of relay 1 of a given individual is shown in Figure 7.

It is illustrated by the simulation results in Table 4 that the protective relays can remove all the three-phase short-circuited faults quickly, given that the coordination constraint of primary/backup protective relays is respected. The coordination results between primary and backup protective relays are shown in Table 5. The line with crosses in Figure 5 represents the objective value of the best individual, although the line with stars represents the objective value of a given individual. The optimal objective value and the objective value of a given individual have clearly improved from generations 1 to 30. In Figure 6, the mismatch of protective relays between the best individual and a given individual is shown; the black line with crosses represents the mismatch of the best individual in each generation, whereas the line with star labels represents the mismatch of a given individual in each generation. It can be seen from Figure 6 that the best individual meets the coordination constraints in the entire evolution process of the DE algorithm, and a given individual could also meet the coordination constraints after several generations. In Figure 7, the changes of T_{M1} in relay 1 for a given individual is shown. The results for the protective relay coordination become stable after 40 generations.

Furthermore, when the outputs of DGs change in the distribution system, an ideal solution is to find a set of relay setting values that meet system operating requirements. However, in actual large-scale distribution systems, the situations are usually very complicated, and it is very difficult, if not impossible, to find a single optimal solution suitable for all system operating conditions. Assuming that there are N_{DG} distributed generators in the distribution system and N_P situations for the output of each DG, there will be ${N_P}^{N_{DG}}$ optimal solutions for all the operating conditions, and the optimal solution for each situation can be calculated beforehand. In general, the larger the N_P is, the more accurate the result will be.

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5. CONCLUDING REMARKS

Distributed generations can bring many benefits in economic, technological, and environmental aspects but, at the same time, result in many challenges, of which one of the most important is the coordination of protective relays. When DGs are connected in a distribution system, both the direction and the distribution of the power flow and fault current in the distribution system could change significantly, such that the traditional protection scheme can no longer work properly. Hence, there is a demand for new protection schemes.

In this work, the optimal coordination problem of protective relays in distribution systems with DGs is formulated as an MINLP problem and solved by the well-established DE algorithm. The feasibility and efficiency of the proposed method has been demonstrated by a sample system.

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