Coordination of Directional Overcurrent Relays Using Seeker Algorithm

Turaj Amraee

Abstract—**Coordination of directional overcurrent relays in a multiloop subtransmission or distribution network is formulated as an optimization problem. In this paper, the coordination of directional overcurrent relays is formulated as a mixed-integer nonlinear programming problem and is then solved by a new seeker optimization technique. Based on the act of human searching, in the proposed seeker technique, the search direction and step length are determined in an adaptive way. The proposed method is implemented in three different test cases. The results are compared with previously proposed analytic and evolutionary approaches.**

Index Terms—**Coordination, directional overcurrent relay, optimization, seeker algorithm.**

I. Introduction

OVERCURRENT protection could be used as the primary protection in distribution or subtransmission networks. Directional overcurrent protection is necessary for ring or multiple source circuits to limit relay tripping for faults in only one direction. The directional relaying is carried out to provide relay coordination between all of the relays that can see the same fault. The aim of the coordination problem is to find the optimal time dial setting and current plug setting of the relays subject to some constraints. These constraints range from relay characteristics to the topological changes of the network. Generally, the coordination problem is a mixed-integer nonlinear programming problem which could be solved by well-known mathematical or evolutionary techniques.

A. Motivation and Problem Description

The coordination problem could be formulated as a linear or nonlinear programming problem. In the linear model, only the time dial settings are optimized and the pickup current settings are fixed at values between the maximum load current and minimum fault current. However, in the nonlinear programming approach, based on the relay characteristic, time dial and pickup current settings are optimized simultaneously. Also, the discrete natures of the settings add more complexity to the coordination problem. Indeed, the coordination problem is a mixed-integer nonlinear programming problem. Due to the uncertainties of load and topological changes, the obtained settings are not optimal over all possible scenarios. Therefore, the coordination problem should be modified to consider all possible scenarios. The pickup setting of the relay remains between the upper and lower values at which all short circuits in the line section are seen. The pickup setting should be above the largest possible load current and below the minimum short-circuit current, with a security margin. Each relay has two main and backup zones. The setting should also provide backup protection for neighbor feeders.

The purpose of the time dial setting is to enable relays to coordinate with each other. By providing a family of curves, two or more relays, seeing the same fault, can operate at different times. Therefore, the main goal of the coordination problem is to find optimal time dial setting (TDS) and plug multiplier setting (PMS) with a minimum operating time of primary relays and under topological and transient changes of network configurations. Therefore, there is an evident need to improve the overcurrent coordination problem to find optimal and robust settings under topological or operational changes in actual power systems. This need motivates the work reported in this paper.

B. Literature Review

Various approaches have been proposed to solve the directional overcurrent coordination problem. They could be categorized in two different approaches. The first approach is based on topological analysis, including graph-theoretic and functional dependencies techniques. In graph-theoretic methods, the concept of breakpoint has been used [1]–[3]. In [1], the concept of linear graph theory has been extended to identify and analyze all simple loops of the network in both directions considering the minimum set of breakpoints and all primary and backup relay pairs. In the functional dependencies method, which is a systematic topological analysis technique, the constraints on the relay settings are formulated by a set of functional dependencies [3].

The second category is based on the optimization techniques in which the coordination problem is formulated as a linear programming problem and the TDSs are then determined via linear programming solvers for fixed values of the pickup settings [4].

The optimization problem could be solved by analytic methods (e.g., Simplex method) [4]–[6] or evolutionary techniques [7]–[10]. In the linear programming approach, the TDS is optimized. To optimize time dial and pickup current settings simultaneously, the coordination problem will be a nonlinear programming model. Recently, the applications of evolutionary techniques have been used in optimal coordination of directional overcurrent relays, genetic-algorithm (GA)-based methods [7]–[9], and the particle swarm optimization (PSO) algorithm [10], [11]. They have been used to solve the overcurrent coordination problem.

Manuscript received July 17, 2011; revised January 25, 2012; accepted February 24, 2012. Date of publication April 10, 2012; date of current version June 20, 2012. Paper no. TPWRD-00606-2011.

The author is with the Faculty of Power Engineering, K. N. Toosi University of Technology, Tehran 1431714191, Iran (e-mail: amraee@eetd.kntu.ac.ir).

Digital Object Identifier 10.1109/TPWRD.2012.2190107

The major weakness of the previously proposed methods, including mathematical and evolutionary approaches, lies in the risk of being trapped in local optimal settings especially under topological changes such as transient changes (i.e., the relay opens at one end of the line section) in actual networks.

C. Contributions

Any directional overcurrent coordination method should satisfy the following requirements.

1) R1: The total operating times of primary relays should be minimized while maintaining coordination among all relays.
2) R2: The pickup and time dial settings should be robust under all possible topological and operational scenarios.
3) R3: The optimization technique should be capable of finding the near-global optimal settings.

The gap that this paper intends to fill is the improvement of the third requirements in addition to the other requirements. Regarding this issue, the coordination problem is formulated as an optimization problem and is then solved by a new seeker algorithm. In the proposed seeker technique, based on the act of human searching, the search direction and related step length are determined in an adaptive way. Also, the concept of seeker mutation enables the seeker algorithm to escape from local optima. The obtained results are compared with other previously proposed analytic and evolutionary approaches.

D. Paper Organization

The rest of this paper is organized as follows. In Section II, the structure and formulation of the directional overcurrent coordination problem are described. The details of the new seeker algorithm are described in Section III. The simulation results of applying the proposed method over three test systems are presented in Section IV. Finally, the conclusions are provided in Section V.

II. Problem Formulation

The coordination of directional overcurrent relays in a multiloop system is formulated as an optimization problem. The coordination problem, including objective function and constraints, should satisfy all three aforementioned requirements.

A. Objective Function

The aim of the coordination problem is to minimize the total weighted sum of operating times of primary relays as follows:

$$\min_{\mathrm{PTS_i},\mathrm{TDS_i}} z = \sum_{i=1}^{m} W_i T_{ik} \tag{1}$$

where variables PTS_i and TDS_i stand for pickup tap setting and time dial setting of the ith relay, respectively. The operating time of the ith relay at location k (i.e., T_{ik}) is defined as

$$T_{ik} = f_i(I_{Pi}, I_{ik},) \times \mathrm{TDS}_i \tag{2}$$

where I_{ik} is the short-circuit current seen by the ith relay for the fault at location k. It should be noted that the goal of the coordination problem is to minimize the total weighted sum of the operating times of primary relays for faults at their associated zones. Therefore, the objective function is written as follows:

$$\min_{\mathrm{PTS_i},\mathrm{TDS_i}} z = \sum_{i=1}^{m} w_i T_{ii}. \tag{3}$$

Inverse time inverse definite minimum time (IDMT) characteristics are selectable from a choice of some IEC/IEEE curves conforming to the following formula:

$$T_{ik} = \mathrm{TDS}_i \left(\frac{K}{\left(\frac{I_{ik}}{I_{Pi}}\right)^{\alpha} - 1} + L \right) \tag{4}$$

where K and α are constant parameters. For IEC curves, L is zero. For standard inverse-type relays, the IDMT characteristics are assumed as $L = 0, \alpha = 0.02, k = 0.14$. Another formulation has been proposed to approximate the relay characteristic called the Sachdev nonlinear model [5].

$$T_{ik} = f_1(\mathrm{TDS}_i) \times f_2(I_{Pi}, I_{ik}) \tag{5}$$

where

$$f_1(\mathrm{TDS}_i) = \sum_{j=0}^{3} b_j \times (\mathrm{TDS}_i)^j \tag{6}$$

$$f_2(I_{Pi}, I_{ik}) = \sum_{j=0}^{4} \frac{a_j}{(I_{ik}/I_{Pi} - 1)^j} \tag{7}$$

where b_j and a_j are constants. Tap settings is used to adjust the minimum current in the relay for which the relay will just pick up. This provides great flexibility in the relay application and permits the same relay to be used at many locations. The concept of relay pickup tap setting could be formulated by

$$\mathrm{PTS}_i = I_{Pi}/(R_{Ci}) \tag{8}$$

where I_{Pi} is the primary pickup current and R_{Ci} stands for the CT ratio.

B. Constraints

The coordination problem has two types of constraints, including the constraints of the relay characteristic and coordination constraints. Relay constraints include limits of relay operating time and settings. Coordination constraints are related to the coordination of primary and backup relays.

1) Constraint of Relay Operating Time: The operating time of a relay is a function of the pickup current setting and the fault current seen by the relay. Based on the type of relay, the operating time is determined via standard inverse curves or analytic formula. The bounds on operating time are expressed by

$$T_{ik}^{\min} \le T_{ik} \le T_{ik}^{\max}, \quad i = 1, \dots, m \tag{9}$$

where $T_{ik}^{\min}$ and $T_{ik}^{\max}$ are the minimum and maximum operating times of the ith relay at the kth location.

2) Constraint of Time and Current Settings: The limits on TDS and PTS are expressed by

$$\mathrm{TDS}_i^{\min} \le \mathrm{TDS}_i \le \mathrm{TDS}_i^{\max}, \quad i = 1, \ldots, m \qquad (10)$$
$$\mathrm{PTS}_i^{\min} \le \mathrm{PTS}_i \le \mathrm{PTS}_i^{\max}, \quad i = 1, \ldots, m. \qquad (11)$$

For phase relays, determining the maximum load current and minimum fault current considering engineering experiences and planning studies for different network topologies is required. The pickup current should be greater than the largest possible load currents and lower than the minimum fault current with a reasonable security margin. This is the tradeoff between the security and dependability features of the relay.

3) Constraint of Coordination: The operating time of a backup relay should be selected to be greater than the operating time of the related primary relay. An intentional time margin called the coordination time interval (CTI) is added to the operating time of the first backup relays. If for a given fault at location k, the jth relay may be the first backup of the ith relay, the coordination constraint could then be expressed by

$$T_{jk} \ge T_{ik} + CTI, \quad i = 1, \ldots, m. \qquad (12)$$

For transient topologies where one relay of a zone has operated, the coordination constraint should be satisfied without considering the tripping sequence

$$T_{jk}^{tr} \ge T_{ik}^{tr} + CTI, \quad i = 1, \ldots, m \qquad (13)$$

where T_{jk}^{tr} is the value of T_{jk} under transient topology. It should be noted that T_{jk}^{tr} is determined via (4) in which the magnitude of I (i.e., fault current magnitude in normal configuration) is replaced with I^{tr} (i.e., fault current magnitude in the transient configuration). The value of CTI varies from 0.2 to 0.3 s.

4) Topological Changes: By considering all probable scenarios of topological changes of the network, the optimal setting is the setting that provides the minimum total operating time for all possible configurations.

III. Seeker Optimization Technique

Seeker optimization is a computational algorithm which imitates the behavior of human searching considering its memory, experience, uncertainty reasoning, and social learning [12]. Some applications of the seeker algorithm could be found in [12]–[14]. All evolutionary techniques are initialized by generating a population of random individuals. Here, each individual of the population is called a seeker. Total search space or population could be divided randomly into some subpopulations. All subpopulations share their findings to escape from the local optimum. The key parts of seeker optimization algorithm are the procedure of determining search direction and step length. In analytic gradient-based optimization techniques, the search direction and step length are determined based on the derivatives of the objective function and constraints. In evolutionary optimization techniques, the search direction and step length are determined only based on the values of objective functions with penalty terms related to constraints. The major parts of the seeker optimization technique will be described.

A. Search Direction

In a population-based search, such as the human search, each individual shows three different behaviors: 1) self-interest or egotistic behavior; 2) group-interest or altruistic behavior; and 3) proactiveness behavior [12]. Each seeker or individual in a population has two extreme types of cooperative behavior. The egotistic behavior is entirely proself and the altruistic behavior is entirely progroup [12]. The position of each seeker is updated as follows:

$$X_i(t+1) = X_i(t) + \alpha_i(t) \times d_i(t), \quad i = 1, \ldots, N_{pop} \quad (14)$$

where $X_i = [X_{i1}, X_{i2}, \ldots, X_{iD}]$, $\alpha_i = [\alpha_{i1}, \alpha_{i2}, \ldots, \alpha_{iD}]$, and $d_i = [d_{i1}, d_{i2}, \ldots, d_{iD}]$ refer to the optimization variable with dimension D, individual step length, and search direction, respectively. The search direction has four components which are determined as follows.

- Personal Direction
  In a population, each seeker is uniformly self-interested; in other words, each seeker has a direction toward his or her best position; this direction is expressed as follows:

  $$d_{i,p}(t) = p_{i,best}(t) - X_i(t) \quad i = 1, \ldots, N_{pop} \qquad (15)$$

  where $X_i(t)$ and $p_{i,best}(t)$ are the current position and historical best position of the ith seeker. $d_{i,p}(t)$ is the search direction toward personal best position of the seeker.
- Local and global directions
  Based on the simulation of social behavior of a groups of agents, each seeker has a progroup behavior. This cooperative behavior could be represented by two directions toward the local and global best positions. The local best position is the best position in each subpopulation, and the global best position is the best position among all seekers in all subpopulations. These two directions are formulated via (16) to (17).

  $$d_{i,l}(t) = l_{\mathrm{k,best}}(t) - X_i(t) \quad i = 1, \ldots, N_{\mathrm{pop}} \qquad (16)$$
  $$d_{i,g}(t) = g_{\mathrm{best}}(t) - X_i(t) \quad i = 1, \ldots, N_{\mathrm{pop}} \qquad (17)$$

  where $l_{\mathrm{k,best}}(t)$ is the local best position of the ith seeker in the kth subpopulation. $g_{\mathrm{best}}(t)$ is the global best position in the population.
- Historical direction
  Each seeker has a memory that retains the best experience. In other words, each seeker could adjust its future direction toward the global solution based on the past experiences obtained during searching the solution space. This proactive learning behavior is modeled by

  $$d_{\mathrm{i,pro}}(t) = X_i(t_1) - X_i(t_2) \quad i = 1, \ldots, N_{\mathrm{pop}} \qquad (18)$$

  where $t_1, t_2 \in \{t, t-1, t-2\}$, and $X_i(t_1)$ is the better solution.

  The overall direction is determined based on a random combination of all directions. The actual search direction of the ith seeker, (i.e., $d_i(t) = [d_{i1}, d_{i2}, \ldots, d_{iD}]$), is determined based on a compromise among the aforementioned four components of search direction. The overall direction of the jth element of the search direction $d_i(t)$ is selected by the following proportional rule [12]:

$$d_{ij} = \begin{cases} 0, & \text{if } r_j \le p_j^0, \\ -1, & p_j^0 \le r_j \le p_j^0 + p_j^1 \\ 1, & p_j^0 + p_j^1 \le r_j \le 1 \end{cases} \tag{19}$$

where d_{ij} refers to the jth dimension of the ith seeker and r_j is a uniform random number between $[0, 1]$, and p_j^m, $m \in \{0, 1, -1\}$ is defined as follows. In the set $\{d_{ij,p}, d_{ij,l}, d_{ij,g}, d_{\mathrm{ij,pro}}\}$, $p_j^{(m)}$ is the percent of the number m or $p_j^{(m)} = (\text{number of } (m))/4$.

B. Step Length

In analytic gradient-based optimization algorithms, the step length or learning factor could be adjusted in an adaptive way. In other words, near the extremum, the step length should be shorter and vice-versa. In evolutionary population-based optimization techniques, such as the human search, the step length toward the optimal point could be interpreted as a fuzzy judgment. Here, in the fuzzification step, a linear membership function and in the defuzzification step, a bell-type membership function are used. To design a fuzzy rule for step-length determination, all the fitness values in the population are sorted from smallest to largest. A number is then assigned to each seeker based on its rank in the population. This number (i.e., $s \in s = 1, \ldots, N_{\mathrm{pop}})$) is used as the input of the fuzzy system with a linear membership function as follows:

$$\mu_i = \mu_{\max} - \frac{N_{\mathrm{pop}} - R_i}{N_{\mathrm{pop}} - 1}(\mu_{\max} - \mu_{\min}) \quad i = 1, \ldots, N_{\mathrm{pop}} \tag{20}$$

where μ_i and R_i are the membership value and the rank of the ith seeker in the sorted population, respectively. The maximum and minimum membership values occur at the global best and the worst positions in the population, respectively. Here, a bell membership function as $\mu_{\alpha_{ij}} = e^{(\alpha_{ij}^2/-2\sigma_j)}$ is used. Based on the bell function, the membership values for the members outside the $[-3\sigma \quad +3\sigma]$ are fixed at $\mu_{\min}$. The value of σ as an indicator of the search radius is a random vector which is determined as

$$\sigma = w \cdot (X_{best} - X_{\mathrm{rand}}) \tag{21}$$

where X_{best} is the best seeker in the same subpopulation. The weighting factor w is used to decrease the step length toward the future

$$w(t) = w_{\max} - \frac{w_{\max} - w_{\min}}{t_{\max}} \cdot t \tag{22}$$

where t is the iteration number.

Finally, the step length will be defuzzified using the bell function as follows:

$$\alpha_{ij} = \sigma_j \sqrt{-log(rand(\mu_i, 1))} \tag{23}$$

where $\mathrm{rand}(\mu_i, 1)$ generates a random number in the interval $[\mu_i, 1]$.

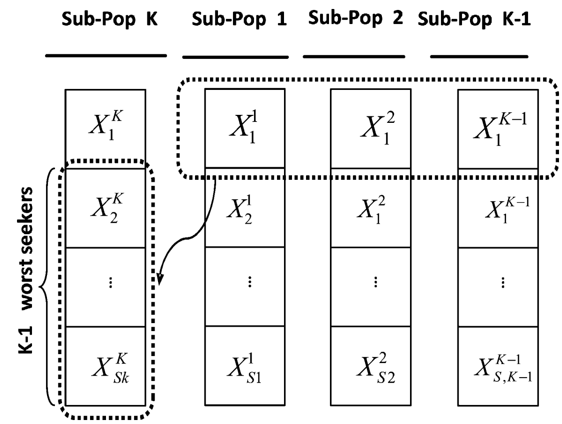

Fig. 1. Mechanism of the intersubpopoulation learning.

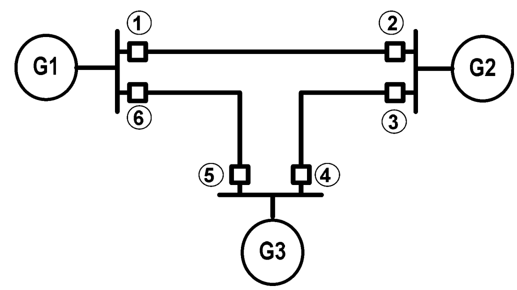

Fig. 2. Single-line diagram of the three-bus test case.

C. Seeker Mutation

Although the addition of the global search component to the overall search direction reduces the probability of being trapped in local optimum, it is beneficial to add an interpopulation learning mechanism. Suppose that there are K subpopulations. The $K - 1$ worst seekers in each subpopulation are replaced by the best positions of the remaining $K - 1$ subpopulations. For example, if there are three subpopulations, the two worst seekers of each subpopulation are replaced with the best seekers of the two remaining subpopulations as shown in Fig. 1.

D. Steps of the Seeker Algorithm

The proposed seeker algorithm is carried out in the following steps.

Step 1) Generate an initial population of seekers with a size of N_{pop}.
Step 2) Split the population in K different subpopulations.
Step 3) Set *iteration* = 1.
Step 4) Evaluate the *fitness function* for each seeker.
Step 5) If the maximum number of iteration is reached, then end; else continue.
Step 6) Determine the *personal best*, *local best*, and *global best positions*.
Step 7) Calculate the four components of the search direction.
Step 8) Calculate the *step length* for all seekers.
Step 9) Update the position of each seeker.

TABLE I
SHORT-CIRCUT RESULTS,THREE-BUS SYSTEM

Primary Relay	Fault Current(A)	Backup Relay	Fault Current(A)
Normal Configuration			
1	1978.90	5	175.00
2	1525.70	4	545.00
3	1683.90	1	617.22
4	1815.40	6	466.17
5	1499.66	3	384.00
6	1766.30	2	145.34
Transient Configuration			
1	2075.0	5	400.70
2	1621.7	4	700.64
3	1779.6	1	760.17
4	1911.5	6	622.65
5	1588.5	3	558.13
6	1855.4	2	380.70

Step 10) Mutate the population using the intersubpopulation learning strategy.
Step 11) Construct the new population, increase the *iteration* and go to Step 4).

IV. MINLP ALGORITHM

In this paper, the mixed-integer nonlinear programming is solved using a standard branch-and-bound algorithm (SBB). SBB is a new solver for mixed-integer nonlinear programming (MINLP) models. It is based on a combination of the standard branch-and-bound method known from mixed integer linear programming and some of the standard NLP solvers already supported by GAMS [15].

V. SIMULATION RESULTS

The proposed algorithm is simulated over three different test cases. In each case, the obtained results are compared with previously proposed algorithms. The effectiveness of the proposed seeker algorithm is verified for continuous and discrete (i.e., mixed-integer) models. In this paper, the coordination problem is carried out for phase relays. It should be noted that for the coordination of ground relays, the same procedure is followed. Due to general similarity of the standard IDMT curves for both phase and ground relays (i.e., in view of linearity or nonlinearity of the objective function and related constraints), the simulations are carried out only for phase relays. A computer program is developed to implement the seeker algorithm using Matlab, and executed on a Pentium IV 3.06-GHz PC with 512-MB RAM.

A. Case 1: Three-Bus Test Case

In this case, the proposed algorithm is simulated for a three-bus test case. The results are presented for linear (i.e., fixed PTS and continuous TDS) and mixed-integer nonlinear (i.e., discrete PTS and continuous TDS) models.

- Linear model
  The proposed algorithm is simulated over a three-bus test case. Data of this test case could be found in [4]. To make a clear comparison, the results of short-circuit analysis for 3ϕ faults at the midpoint of lines are given in Table I. The transient configuration refers to the configuration in which the primary relay has opened the circuit breaker at one end of the line. The value of CT ratio and related tap settings is given in Table II. To make a clear comparison, the lower limit of time dial setting is fixed at 0.1 s. Therefore, the coordination problem is a linear programming problem. For this test case, the seeker parameters are assumed as $(\mu_{\min}, \mu_{\max})$ = (0.95,0.0111), $(w_{\min}, w_{\max})$ = (0.1,0.9), and $N_{\text{pop}} = 50$. The results obtained by the proposed method and the previously proposed methods are given in Table III. All three methods give the same results. Regarding the convergence time, the time taken by the seeker algorithm to reach the optimal setting is about 6.45 s after 45 iterations.
- Mixed-integer nonlinear model
  Now it is assumed that the pickup tap setting is a discrete variable between 1.5–5 in steps of 0.5. The optimization parameters are assumed as given in the previous case. The new results are given in Table IV. A standard branch-and-bound algorithm has been used to solve the resulting mixed-integer nonlinear programming problem. It can be seen that the proposed seeker technique gives better settings rather than the analytic SBB procedure. The time taken by the seeker algorithm to reach the optimal setting is about 10.45 s after 85 iterations.

TABLE II
PICKUP TAP SETTING AND CT RATIO, THREE-BUS SYSTEM

Relay No	CT Ratio	Pickup Tap Setting
1	300/5	5.0
2	200/5	1.5
3	200/5	5.0
4	300/5	4.0
5	200/5	2.0
6	400/5	2.5

TABLE III
TIME DIAL SETTINGS, THREE-BUS SYSTEM, LINEAR MODEL

Relay No	Time Dial Setting (second)		
	Simplex Method([4])	PSO Algorithm([11])	Proposed Algorithm
1	0.1000	0.1000	0.1000
2	0.1364	0.1364	0.1364
3	0.1000	0.1000	0.1000
4	0.1000	0.1000	0.1000
5	0.1298	0.1298	0.1298
6	0.1000	0.1000	0.1000
Total Operating Time $\sum T_{ii}$	1.9258	1.9258	1.9258

TABLE IV
TDSS, THREE-BUS SYSTEM, MINLP MODEL

Relay No	MINLP (SBB)		Proposed Algorithm	
	TDS	PTS	TDS	PTS
1	0.1510	1.5	0.1070	2.5
2	0.1280	1.5	0.1080	2.0
3	0.1300	2.0	0.1000	3.0
4	0.1040	2.5	0.1000	2.5
5	0.1060	2.5	0.1000	2.5
6	0.1000	2.0	0.1120	1.5
Total Operating Time $\sum T_{ii}$	1.727		1.599	

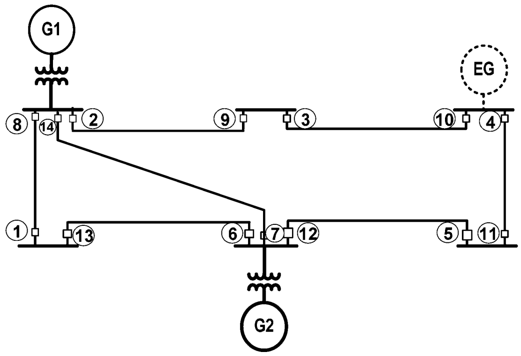

Fig. 3. Single-line diagram of the eight-bus test case.

TABLE V
NEAR-END 3ϕ SHORT-CIRCUIT RESULTS, EIGHT-BUS SYSTEM

Primary Relay	Fault Current(A)	Backup Relay	Fault Current(A)
1	3232	6	3232
2	5924	1	996
2	5924	7	1890
3	3556	2	3556
4	3783	3	2244
5	2401	4	2401
6	6109	5	1197
6	6109	14	1874
7	5223	5	1197
7	5223	13	987
8	6093	7	1890
8	6093	9	1165
9	2484	10	2484
10	3883	11	2344
11	3707	12	3707
12	5899	13	987
12	5899	14	1874
13	2991	8	2991
14	5199	1	996
14	5199	9	1165

TABLE VI
OPTIMAL TDS, 8-BUS SYSTEM

Relay No	GA [9]		Hybrid GA-LP [9]		Proposed Algorithm	
	TDS	PTS	TDS	PTS	TDS	PTS
1	0.29	1.0	0.3043	1.0	0.113	2.0
2	0.31	2.5	0.2917	2.5	0.260	2.5
3	0.26	2.5	0.2543	2.5	0.225	2.5
4	0.19	2.5	0.1851	2.5	0.160	2.5
5	0.18	1.5	0.1700	1.5	0.100	2.5
6	0.26	2.5	0.2711	2.5	0.173	2.5
7	0.54	0.5	0.5316	0.5	0.243	2.5
8	0.24	2.5	0.2387	2.5	0.170	2.5
9	0.17	2.0	0.1856	2.0	0.147	2.5
10	0.19	2.5	0.1895	2.5	0.176	2.5
11	0.21	2.5	0.2014	2.5	0.187	2.5
12	0.30	2.5	0.2890	2.5	0.266	2.5
13	0.23	1.5	0.2297	1.5	0.114	2.0
14	0.51	0.5	0.5278	0.5	0.246	2.5
Total Operating Time $\sum T_{ii}$	11.001		10.9499		8.4270	

B. Case 2: Eight-Bus Test Case

The proposed algorithm is simulated over an eight-bus test system. The system data could be found in [10]. The test case has 14 relays as shown in Fig. 3. The TDSs range continuously from 0.1 to 1.1. To make a clear comparison, seven discrete pickup tap settings (i.e., 0.5, 0.6, 0.8, 1.0, 1.5, 2.0, and 2.5) are assumed. The ratio of current transformer of relays (1, 2, 4, 5, 6, 8, 10, 11, 12, 13) and (3,7, 9, 14) are assumed as (1200:5) and (800:5), respectively. A coordination interval of 0.3 s is considered. The short-circuit current for near-end 3ϕ short-circuit faults is given in Table V. For this test case, the seeker parameters are assumed as $(\mu_{\min}, \mu_{\max}) = (0.95, 0.0111)$, $(w_{\min}, w_{\max}) = (0.1, 0.9)$ and $N_{\text{pop}} = 100$. According to Table VI, it can be seen that the proposed method gives a lower total operating time for primary relays. The time taken by the seeker algorithm to reach the optimal setting is about 50.45 s after 169 iterations.

TABLE VII
CT RATIO FOR THE RELAYS OF A 15-BUS SYSTEM

Relay No	CT Ratio
18-20-21-29	1600/5
2-4-8-11-12-14-15-23	1200/5
1-3-5-10-13-19-36-37-40-42	800/5
6-7-9-16-24-25-26-27-28-31-32-33-35	600/5
17-22-30-34-38-39-41	400/5

TABLE VIII
NEAR-END 3ϕ SHORT-CIRCUIT RESULTS, 15-BUS SYSTEM

Primary	I(A)	Backup	I(A)	Primary	I(A)	Backup	I(A)
1	3621	6	1233	20	7662	30	681
2	4597	4	1477	21	8384	17	599
2	4597	16	743	21	8384	19	1372
3	3984	1	853	21	8384	30	681
3	3984	16	743	22	1950	23	979
4	4382	7	1111	22	1950	34	970
4	4382	12	1463	23	4910	11	1475
4	4382	20	1808	23	4910	13	1053
5	3319	2	922	24	2296	21	175
6	2647	8	1548	24	2296	34	970
6	2647	10	1100	25	2289	15	969
7	2497	5	1397	25	2289	18	1320
7	2497	10	1100	26	2300	28	1192
8	4695	3	1424	26	2300	36	1109
8	4695	12	1463	27	2011	25	903
8	4695	20	1808	27	2011	36	1109
9	2943	5	1397	28	2525	29	1828
9	2943	8	1548	28	2525	32	697
10	3568	14	1175	29	8346	17	599
11	4342	3	1424	29	8346	19	1372
11	4342	7	1111	29	8346	22	642
11	4342	20	1808	30	1736	27	1039
12	4195	13	1503	30	1736	32	697
12	4195	24	753	31	2867	27	1039
13	3402	9	1009	31	2867	29	1828
14	4606	11	1475	32	2069	33	1162
14	4606	24	753	32	2069	42	907
15	4712	1	853	33	2305	21	1326
15	4712	4	1477	33	2305	23	979
16	2225	18	1320	34	1715	31	809
16	2225	26	905	34	1715	42	907
17	1875	15	969	35	2095	25	903
17	1875	26	905	35	2095	28	1192
18	8426	19	1372	36	3283	38	882
18	8426	22	642	37	3301	35	910
18	8426	30	681	38	1403	40	1403
19	3998	3	1424	39	1434	37	1434
19	3998	7	1111	40	3140	41	745
19	3998	12	1463	41	1971	31	809
20	7662	17	599	41	1971	33	1162
20	7662	22	642	42	3295	39	896

C. Case 3: 15-Bus Test Case

The proposed technique is implemented in a 15-bus test network. This case is a highly distributed generation (DG) penetrated distribution network as shown in Fig. 4. Each generator has a synchronous reactance of x =15% with 15 MVA and 20-kV ratings. The external grid has 200-MVA short-circuit

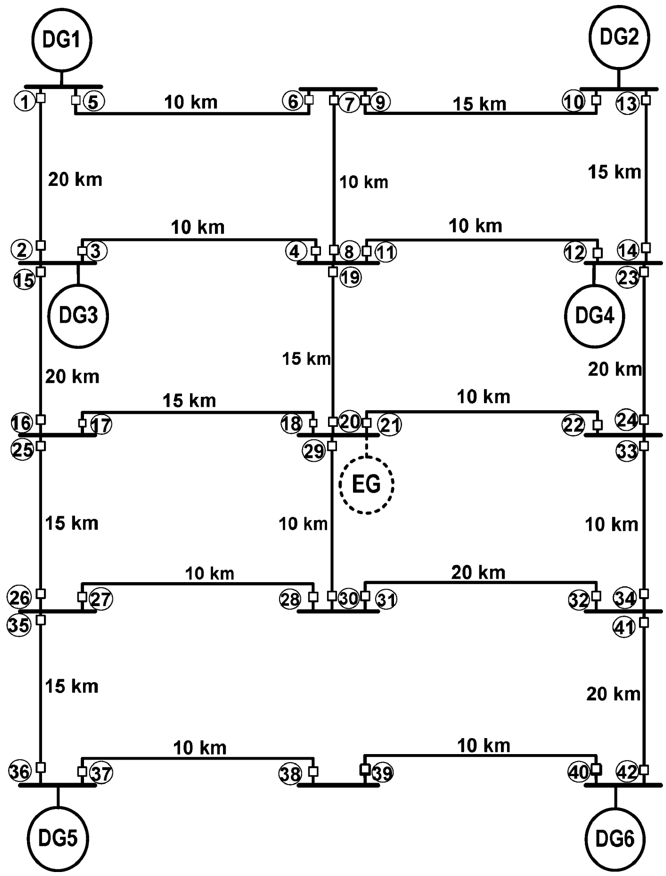

Fig. 4. Single-line diagram of the 15-bus network.

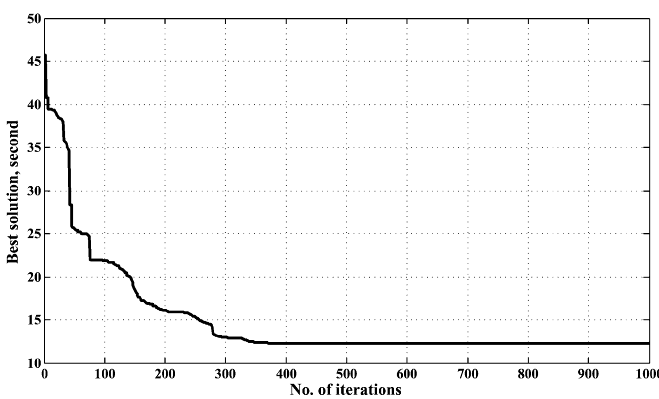

Fig. 5. Convergence of the seeker algorithm to the final solution, case 3.

capacity. The reactance of each line section is $Z = 0.19 + J0.46\ \Omega/\mathrm{km}$. The short-circuit analysis for near-end 3ϕ faults and based on the International Electrotechnique Commission standard are given in Table VIII. The test case has 42 relays and 82 backup-primary pairs. It is assumed that the TDS is greater than 0.10 s. The pickup tap setting for current pickup varies between 0.5 to 2.5 in steps of 0.5. The resulting mixed-integer nonlinear programming problem is solved using a standard branch-and-bound technique and a new seeker algorithm. For this test case, the seeker parameters are assumed as $(\mu_{\min}, \mu_{\max}) = (0.95, 0.0111)$,, $(w_{\min}, w_{\max}) = (0.1, 0.9)$, and $N_{\mathrm{pop}} = 120$. The optimal settings found by two approaches are given in Tables IX and X. It could be deduced that in case

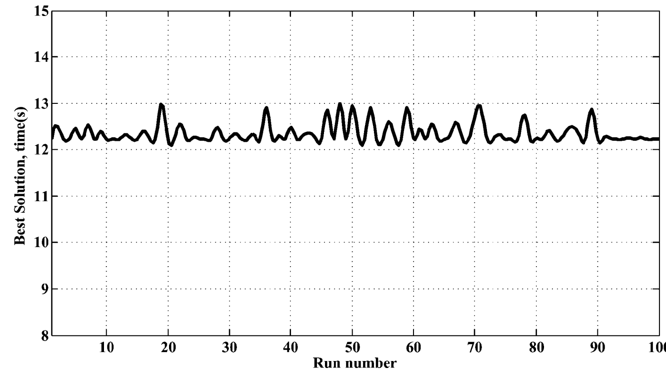

Fig. 6. Variations of the best solution found for 100 different program runs, 15-bus system.

TABLE IX
OPTIMAL SETTINGS OF THE 15-BUS SYSTEM

Relay No	Proposed Algorithm		MINLP (SBB)	
	TDS	PTS	TDS	PTS
1	0.118	1.0	2.5	0.100
2	0.101	1.0	1.5	0.100
3	0.105	2.0	2.0	0.124
4	0.115	1.0	1.5	0.119
5	0.109	2.0	1.5	0.152
6	0.108	2.0	0.5	0.227
7	0.106	2.0	1.5	0.152
8	0.108	1.5	2.0	0.102
9	0.106	2.0	2.5	0.117
10	0.112	1.5	2.5	0.100
11	0.100	1.5	1.5	0.111
12	0.100	1.5	0.5	0.211
13	0.107	2.0	0.5	0.259
14	0.111	1.0	1.5	0.100
15	0.103	1.0	0.5	0.207
16	0.100	1.5	0.5	0.198
17	0.100	2.0	2.5	0.100
18	0.105	1.0	1.5	0.100
19	0.102	2.0	0.5	0.218
20	0.100	1.5	2.0	0.100
21	0.166	0.5	0.5	0.189

TABLE X
OPTIMAL SETTINGS OF THE 15-BUS SYSTEM, CONTINUED

Relay No	Proposed Algorithm		MINLP (SBB)	
	TDS	PTS	TDS	PTS
22	0.109	1.5	2.0	0.100
23	0.109	1.0	0.5	0.188
24	0.100	1.5	2.5	0.100
25	0.103	2.0	0.5	0.258
26	0.112	1.5	2.5	0.100
27	0.104	2.0	1.0	0.185
28	0.105	2.5	2.0	0.136
29	0.104	1.5	2.0	0.100
30	0.101	2.0	0.5	0.217
31	0.100	2.0	1.5	0.138
32	0.105	1.5	2.0	0.100
33	0.100	2.5	2.0	0.137
34	0.107	2.5	1.0	0.196
35	0.103	2.0	2.5	0.109
36	0.100	2.0	1.0	0.183
37	0.103	2.5	1.0	0.213
38	0.106	2.5	1.0	0.214
39	0.103	2.5	1.0	0.198
40	0.104	2.5	2.0	0.152
41	0.104	2.5	2.0	0.146
42	0.104	1.5	1.0	0.160
Total Operating Time $\sum T_{ii}$	12.227		15.335	

of mixed-integer variables, the proposed seeker optimization technique yields better results. While most of the mathematical approaches are guaranteed to converge only under special convexity assumptions, the proposed seeker algorithm could provide superior results for mixed-integer nonlinear programming problems. The computational time to reach the optimal setting is about 406.3 s after 385 iterations. Also, the convergence of the seeker algorithm is illustrated in Fig. 5. One major advantage of the seeker algorithm is its robustness for different runs of the algorithm. Based on Fig. 6, it can be seen that the best solution could be found in a significant number of trials.

VI. Conclusion

Coordination of directional overcurrent relays was formulated as a mixed-integer nonlinear programming problem and was then solved by a new seeker optimization technique. In the proposed seeker technique, based on the act of human searching, the search direction and step length were determined in an adaptive way. The proposed technique was applied over three different cases. The effectiveness of the proposed technique was verified for continuous and discrete variables. The results showed that the proposed seeker technique is capable of finding superior TDS and PMS settings in linear and nonlinear models. The obtained results verified that the proposed seeker covers the weakness of the previously proposed evolutionary techniques.

References

[1] M. Damborg, R. Ramaswami, S. Venkata, and J. Postforoosh, "Computer aided transmission protection system design part I: Alcorithms," *IEEE Trans. Power App. Syst.*, vol. PAS-103, no. 1, pp. 51–59, Jan. 1984.

[2] M. H. Dwarakanath and L. Nowitz, "An application of linear graph theory for coordination of directionalovercurrent relays," in *Proc. Elect. Power Problems—Math. Challenge Conf.*, Seattle, WA, 1980, no. 1, pp. 104–114, SIAM.

[3] L. Jenkins, H. Khincha, S. Shivakumar, and P. Dash, "An application of functional dependencies to the topological analysis of protection schemes," *IEEE Trans. Power Del.*, vol. 7, no. 1, pp. 77–83, Jan. 1992.

[4] A. Urdaneta, R. Nadira, and L. P. Jimenez, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Trans. Power Del.*, vol. 3, no. 3, pp. 903–911, Jul. 1988.

[5] B. Chattopadhyay, M. Sachdev, and T. Sidhu, "An on-line relay coordination algorithm for adaptive protection using linear programming technique," *IEEE Trans. Power Del.* , vol. 11, no. 1, pp. 165–173, Jan. 1996.

[6] H. Abyaneh, M. Al-Dabbagh, H. Karegar, S. Sadeghi, and R. Khan, "A new optimal approach for coordination of overcurrent relays in interconnected power systems," *IEEE Trans. Power Del.*, vol. 18, no. 2, pp. 430–435, Apr. 2003.

[7] F. Razavi, H. A. Abyaneh, M. Al-Dabbagh, R. Mohammadi, and H. Torkaman, "A new comprehensive genetic algorithm method for optimal overcurrent relays coordination," *Elect. Power Syst. Res.*, vol. 78, no. 4, pp. 713–720, 2008.

[8] P. Bedekar and S. Bhide, "Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach," *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 109–119, Jan. 2011.

[9] A. Noghabi, J. Sadeh, and H. Mashhadi, "Considering different network topologies in optimal overcurrent relay coordination using a hybrid GA," *IEEE Trans. Power Del*, vol. 24, no. 4, pp. 1857–1863, Oct. 2009.

[10] H. Zeineldin, E. El-Saadany, and M. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Elect. Power Syst. Res.*, vol. 76, no. 11, pp. 988–995, 2006.

[11] M. Mansour, S. F. Mekhamer, and E.-S. N. El-Kharbawe, "A modified particle swarm optimizer for the coordination of directional overcurrent relays," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1400–1410, Jul. 2007.

[12] C. Dai, Y. Zhu, W. Chen, and X. Zhang, "Seeker optimization algorithm for optimal reactive power dispatch," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1218–1231, Aug. 2009.

[13] B. Shaw1, V. Mukherjee, and S. Ghoshal, "Seeker optimisation algorithm: Application to the solution of economic load dispatch problems," *Inst. Eng. Technol. Gen., Transm. Distrib.*, vol. 5, no. 1, p. 8191, Aug. 2011.

[14] C. Dai, Y. Zhu, and W. Chen, "Seeker optimization algorithm for digital IIR filter design," *IEEE Trans. Ind. Electron.*, vol. 57, no. 5, pp. 1710–1718, May 2010.

[15] Gams Release 2.50, A Users Guide. 1999. [Online]. Available: http://www.gams.com

Turaj Amraee was born in Loristan, Iran, in 1979. He received the Ph.D. degree in power system engineering from Sharif University of Technology, Tehran, Iran, and Grenoble Institute of Technology, Grenoble, France, in 2011.

Currently, he is an Assistant Professor in the Electrical Engineering Department, K.N. Toosi University of Technology, Tehran. His research interests are power system dynamics, system protection schemes, blackouts, and power system operations.