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Coordination of Directional Overcurrent Relays Using the Backtracking Search Algorithm

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The Directional Overcurrent Relays (DOCRs) coordination problem is of paramount importance for power system protection. This paper uses a new metaheuristic method called the Backtracking Search Algorithm (BSA) to solve the DOCRs coordination problem. The coordination problem has been formulated as an optimization problem to minimize the operating time of all the primary relays. The proposed algorithm has been implemented and applied to three test systems including the 6-bus, the 8-bus and the 15-bus test systems. Furthermore, a reliable approach has been developed to compare the results obtained using the proposed BSA with those obtained using other well-known metaheuristics. The results show the superiority of BSA over other methods in solving DOCRs coordination problems.

Keywords: Power system protection; overcurrent relay coordination; optimization; backtracking search algorithm.

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1. Introduction

The directional overcurrent relays (DOCRs) are widely used in modern power systems due to their simplicity and economical benefits. DOCRs are a good technical and economic choice for protection of transmission and distribution power systems [1]. They are used as a secondary protection in transmission power systems and as a primary protection in distribution power systems [2]. Each protection relay needs to be coordinated with other relays to allow for a reliable and safe operation. Therefore, determining the optimal settings of DOCRs is a very challenging problem.

In recent years, many efforts have been made to achieve optimum protection coordination using different optimization algorithms including: evolutionary algorithms in [3], differential evolution in [4], modified differential evolution in [5], self-adaptive differential evolutionary in [6], particle swarm optimization in [7], modified particle swarm optimizer in [8, 9], evolutionary particle swarm optimization in [10], box-muller harmony search in [11], zero-one integer programming approach in [12], covariance matrix adaptation evolution strategy in [13], seeker optimization algorithm in [14], teaching learning-based optimization in [15], and chaotic differential evolution in [16], artificial bee colony in [17], firefly optimization algorithm in [18, 19], modified swarm firefly algorithm in [20], biogeography based optimization in [21], non dominated sorting genetic algorithm in [22] group search optimization in [23], mixed integer optimization using PSO algorithm in [24], interior point method in [25], enhanced backtracking search algorithm in [26], and chaotic firefly algorithm in [27].

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In this paper, a recently developed optimization method called the Backtracking Search Algorithm (BSA) is implemented and applied to the optimal coordination of DOCRs. This algorithm has been developed in 2013 by Civicioglu [28]. Moreover, it is reported in the literature that BSA has been successfully applied to solve some engineering optimization problems like in [29, 30].

In this paper, the optimal coordination of DOCRs is formulated as a non-linear programming (NLP) and as a mixed integer nonlinear programming (MINLP) problem where both Time Dial settings (*TDS*) and Pickup Current (I_P) or Pickup Tap Settings (*PTS*) are determined optimally to minimize the relay operating times. The proposed method is compared against other heuristic methods on various test systems.

The remainder of this paper is organized as follows. Section 2 presents the DOCRs coordination problem formulation. The BSA is presented in section 3. Section 4 presents the simulation results and discussions. The main conclusions are highlighted in section 5.

2. Formulation of the DOCRs Coordination Problem

Generally, the objective of the DOCRs coordination problem is to minimize the total operating time of all primary relays while satisfying the relay setting constraints. Therefore, the objective function (*OF*), can be expressed by:

$$OF = \sum_{i=1}^{N} T^{i} \tag{1}$$

Where *N* is the number of primary relays and T^i is the operating time of the i^{th} relay. The main design settings of the overcurrent relay are the time dial setting, *TDS*, and the pickup current, I_P. The pickup current setting can be a continuous value or a discrete value expressed as the product of current transformer ratio, *CT_Ratio* and the pickup tap settings, *PTS*. Therefore, according to the nature of pickup current setting, the coordination problem can be mathematically formulated as a constrained optimization problem as follows.

2.1. Continuous pickup current setting

Generally, the relays have a standard inverse time-current characteristic according to the IEC standard. In this case, the operating time of a relay can be calculated as follows.

$$T_i = \frac{\alpha \times TDS^i}{\left(\frac{I_F^i}{I_P^i}\right)^{\beta} - \gamma}, \qquad i = 1, 2, \ldots, N \tag{2}$$

Where α, β and γ are constants values. I_F^i is the fault current flowing through the relay R_i for a particular fault located in a particular zone. Therefore, the coordination problem can be formulated as follows.

$$Minmize \quad OF(s) \tag{3}$$

$$Subject \ to:$$

$$T^i_{\min} \le T^i \le T^i_{\max} \tag{4}$$

$$TDS^i_{\min} \le TDS^i \le TDS^i_{\max} \tag{5}$$

$$Ip^i_{\min} \le Ip^i \le Ip^i_{\max} \tag{6}$$

$$T_{backup} - T_{primary} \ge CTI \tag{7}$$

Where s is the design variables, which are the time dial setting, *TDS*, and the pickup current, I_P for all primary relays. T_{backup} and $T_{primary}$ are the operating time of the backup relay and the primary relay, respectively. *CTI* is the minimum coordination time interval to be maintained. For electromechanical relays, the *CTI* varies between 0.30 to 0.40 sec, while for numerical relays it varies between 0.10 to 0.20 sec [13, 14].

It is worth mentioning that the DOCRs coordination problem formulated above is a non-linear programming (NLP) problem where the design variables are self-constrained. However, in order to handle the constraints (4) and (7) the penalty method is used.

2.2. Discrete pickup current setting

In this case, the operating time of a relay can be calculated as follows.

$$OF = \sum_{i=1}^{N} \frac{\alpha \times TDS^i}{\left(\dfrac{I^i_F}{PTS^i \times CT\_Ratio_i} \right)^{\beta} - \gamma}, \qquad i = 1, 2, \ldots, N \tag{8}$$

Therefore, the coordination problem can be formulated as follows.

$$Minmize \quad OF(s) \tag{9}$$

$$Subject \ to:$$

$$T^i_{\min} \le T^i \le T^i_{\max} \tag{10}$$

$$TDS^i_{\min} \le TDS^i \le TDS^i_{\max} \tag{11}$$

$$PST^i_{\min} \le PST^i \le PST^i_{\max} \tag{12}$$

$$T_{backup} - T_{primary} \ge CTI \tag{13}$$

In this case, the design variables, *s*, are the time dial setting, *TDS*, and the pickup tap setting, *PTS,* for all primary relays. It is worth mentioning that the DOCRs coordination problem is formulated in this case as a mixed integer non-linear programming (MINLP) problem where the design variables are self-constrained. However, the constraints (10) and (13) are handled using the penalty method.

3. Backtracking Search Algorithm (BSA)

The BSA is a new evolutionary algorithm and global optimization method developed in [28] for solving real-valued numerical optimization problems. It uses the three basic and well-known EA operators that are selection, mutation and crossover. The main steps of BSA are given in Algorithm 1. BSA is a population based optimization method; thus, it starts by randomly generating a population in the search space. In the Selection–I stage, the historical population that is used for calculating the search direction is determined.

In the Mutation stage, the initial form of the trial population is generated while in the Crossover stage the final form of this trial population is generated. In this stage the best trial individuals for the optimization problem are used to evolve the target population individuals [28]. At the end of the Crossover stage, the individuals that go beyond the search space limits are redefined inside these limits. In the Selection-II stage, the trial population is used to update the population using a greedy selection. More details about the BSA can be found in [28].

Algorithm 1: General structure of BSA [28].

```
1. Initialization
repeat
    2. Selection-I
    Generation of Trial-Population
        3. Mutation
        4. Crossover
    End
    5. Selection-II
until stopping conditions are met
```

4. Application and Results

4.1. Test system 1: the 6-bus test system

The first test system investigated in this paper is the 6-bus test system shown in Figure 1. This system is composed of 6 buses, 3 generators, 3 power transformers, 3 transmission lines and 6 relays.

The short-circuit currents measured by primary and backup relays are given in Table 1. A minimum *CTI* value of 0.3 is selected for this test system. Furthermore, this system has 12 design variables and 6 constraints.

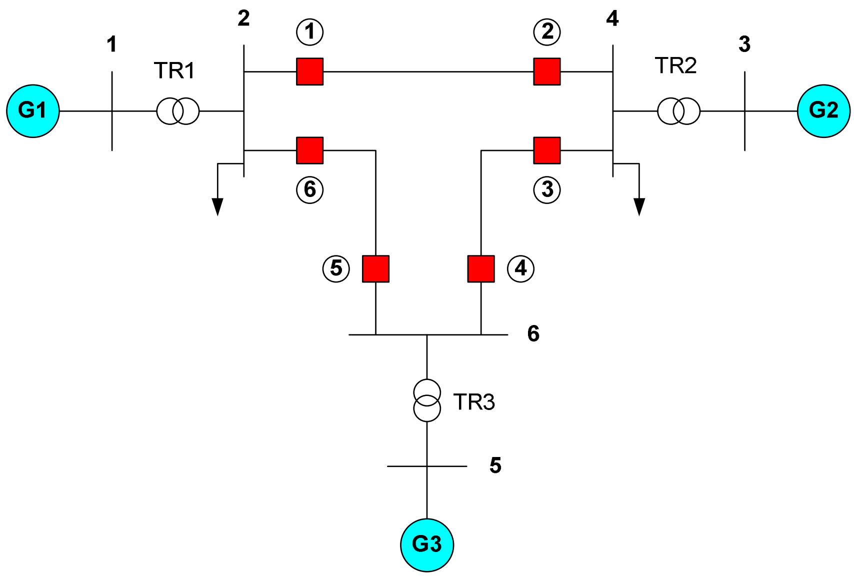

Figure 1: Single-line diagram of the 6-bus test system.

Table 1. Primary/backup relays fault currents for the 6-bus test system.

Primary Relay	I_F (A) (Primary)	Backup Relay	I_F (A) (Backup)
1	2075	5	400.7
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	380.7

Table 2. The main characteristics of the 6-bus test system.

		TDS (sec)		I_P (A)		*PTS* (A)	
Relay	**CT Ratio**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
1	300 / 5	0.1	1.1	90	300	1.5	5.0
2	200 / 5	0.1	1.1	60	200	1.5	5.0
3	200 / 5	0.1	1.1	60	200	1.5	5.0
4	300 / 5	0.1	1.1	90	300	1.5	5.0
5	200 / 5	0.1	1.1	60	200	1.5	5.0
6	400 / 5	0.1	1.1	120	400	1.5	5.0

4.1.1. CASE 1

In this case, the DOCRs coordination problem is formulated as a NLP problem where design variables are *TDS* and I_P. All design variables are continuous, the lower and upper bounds of each variable are given in Table 2.

The BSA is run to solve the DOCRs coordination problem for this case and the optimal results are given in Table 3 and Table 4. A graphical representation of operating times and *CTI* obtained for this case are given in Figure 2.

The results obtained using BSA for this case are compared with those obtained using some popular optimization methods which include: Differential Evolution (DE), Particle Swarm Optimization (PSO), Black Hole (BH), Electromagnetism-Like Mechanism (EM), Biogeography-Based Optimization (BBO) and Harmony search (HS). This comparison shows the excellent performance of the BSA.

Moreover, the convergence trend of the BSA applied to CASE 1 is given in Figure 3 where T_{PR} represents the primary protection time and T_{BR} represents the backup protection time.

Table 3. Obtained results for CASE 1.

Relay	**Prop. BSA**		**DE**		**PSO**		**BH**		**EM**		**BBO**		**HS**	
	***TDS* (sec)**	**I_P (A)**	***TDS* (sec)**	**I_P (A)**	***TDS* (sec)**	**I_P (A)**	***TDS* (sec)**	**I_P (A)**	***TDS* (sec)**	**I_P (A)**	***TDS* (sec)**	**I_P (A)**	***TDS* (sec)**	**I_P (A)**
1	0.100	171.851	0.100	171.851	0.100	202.674	0.417	146.592	0.502	90.085	0.104	171.566	0.129	180.081
2	0.100	60.000	0.100	60.000	0.100	200.000	0.210	70.683	0.358	60.028	0.103	60.820	0.101	65.643
3	0.100	99.309	0.100	99.309	0.100	200.000	0.354	112.843	0.536	60.051	0.112	84.944	0.123	88.366
4	0.100	140.532	0.100	140.532	0.167	90.000	0.324	156.137	0.536	90.885	0.100	143.568	0.117	120.115
5	0.100	60.000	0.100	60.000	0.100	60.000	0.198	87.831	0.369	60.001	0.100	60.354	0.122	60.998
6	0.100	137.585	0.100	137.585	0.100	120.000	0.201	231.916	0.670	120.029	0.107	130.107	0.105	157.249
***OF* (sec)**	**1.474**		**1.474**		**1.495**		**3.160**		**2.764**		**1.516**		**1.661**	

Table 1. Operating times and *CTI* for CASE 1.

Primary Relay	**Operating time (sec)**	**Backup Relay**	**Operating time (sec)**	***CTI* (sec)**
1	0.280	**5**	0.647	0.367
2	0.209	**4**	0.510	0.300
3	0.240	**1**	0.541	0.300
4	0.267	**6**	0.567	0.300
5	0.211	**3**	0.511	0.300
6	0.267	**2**	0.784	0.517

Figure 2. Operating times of primary and backup relays and *CTI* for CASE 1.

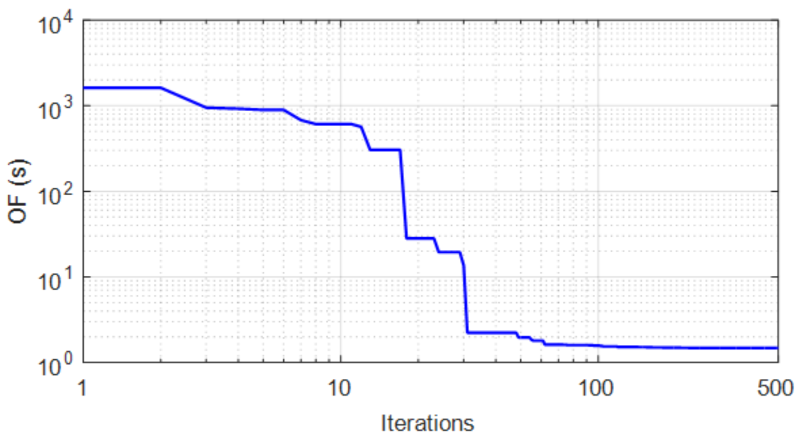

Figure 3. Evolution of the objective function over iterations for CASE 1.

4.1.2. CASE 2

In this second case, the DOCRs coordination problem is formulated as a MINLP problem where design variables are TDS and *PTS*. The *TDS* design variables are continuous whilst the *PTS* design variables are discrete. The lower and upper bounds of each variable are given in Table 2.

The BSA is run to solve the DOCRs coordination problem for this case and the optimal results are given in Table 5, Table 6 and Figure 4. Furthermore, in Table 5, the results obtained using BSA for this case are compared with those obtained using DE, PSO, BH, EM, BBO and HS.

It is worth to mention the excellent performance of the BSA for solving DOCRs coordination problem formulated as mixed-integer nonlinear problems since it gives the minimum value of the operating time.

Table 5. Obtained results for CASE 2.

	Prop. BSA		**DE**		**PSO**		**BH**		**EM**		**BBO**		**HS**	
Relay	***TDS* (sec)**	***PTS* (A)**	***TDS* (sec)**	***PTS* (A)**	***TDS* (sec)**	***PTS* (A)**	***TDS* (sec)**	***PTS* (A)**	***TDS* (sec)**	***PTS* (A)**	***TDS* (sec)**	***PTS* (A)**	***TDS* (sec)**	***PTS* (A)**
1	0.100	3.000	0.100	3.000	0.100	5.000	0.309	3.500	0.188	1.500	0.143	2.000	0.156	2.000
2	0.100	1.500	0.100	1.500	0.100	1.500	0.176	2.000	0.141	1.500	0.100	1.500	0.101	1.500
3	0.100	2.500	0.100	2.500	0.140	1.500	0.355	2.000	0.168	1.500	0.103	2.500	0.114	2.500
4	0.100	2.500	0.133	1.500	0.133	1.500	0.310	3.000	0.157	1.500	0.115	2.000	0.135	2.000
5	0.100	1.500	0.100	1.500	0.103	1.500	0.225	2.000	0.151	1.500	0.105	1.500	0.101	2.000
6	0.100	2.000	0.100	2.000	0.118	1.500	0.305	2.000	0.140	1.500	0.117	1.500	0.109	2.000
***OF* (sec)**		**1.504**		**1.504**		**1.565**		**3.002**		**1.983**		**1.611**		**1.634**

Table 6. Operating times and *CTI* for CASE 2.

Primary Relay	**Operating time (sec)**	**Backup Relay**	**Operating time (sec)**	***CTI* (sec)**
1	0.285	**5**	0.647	0.362
2	0.209	**4**	0.536	0.326
3	0.241	**1**	0.561	0.320
4	0.274	**6**	0.648	0.374
5	0.211	**3**	0.513	0.303
6	0.285	**2**	0.784	0.500

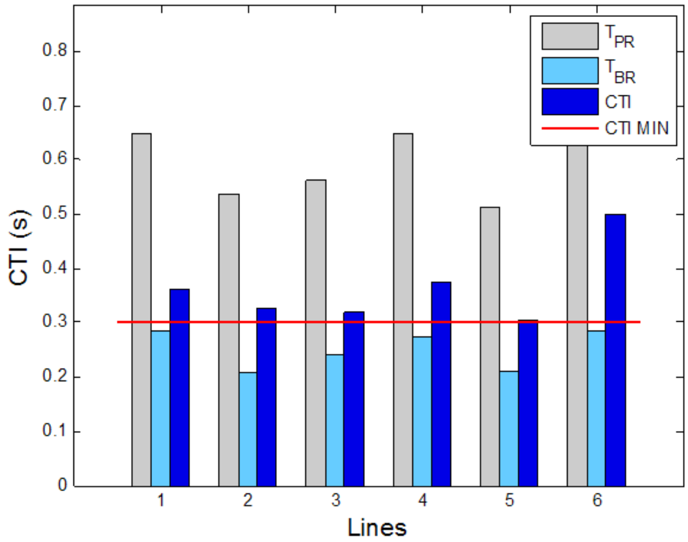

Figure 4: Operating times of primary and backup relays and *CTI* for CASE 2.

4.2. Test system 2: the 8-bus test system

The second system investigated in this paper is the 8-bus test system shown in Figure 5. It is composed of 8 buses, 2 generators, 2 transformers, 7 lines and 14 relays. The short-circuit currents measured by primary and backup relays are given in Table 7.

A minimum *CTI* value of 0.3 is selected for this test system. Furthermore, this system has 28 design variables and 20 constraints.

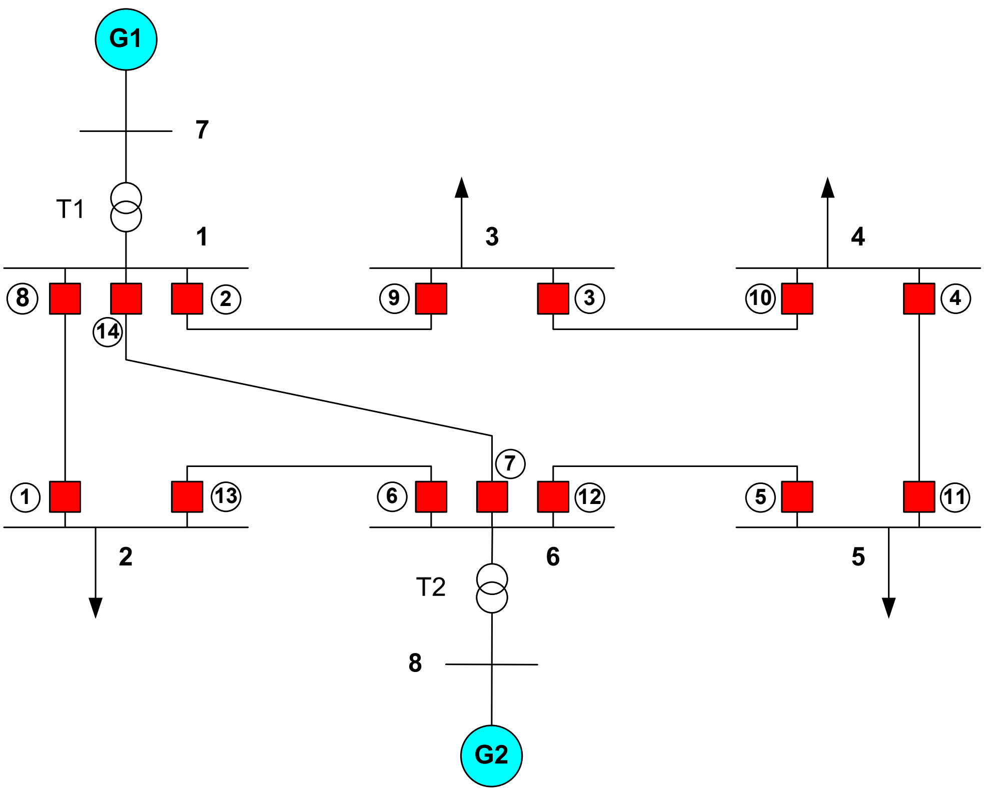

Figure 5. Single-line diagram of the 8-bus test system.

Table 7. Primary/backup relays fault currents for 8-bus test system.

Primary Relay	I_F (A) (Primary)	Backup Relay	I_F (A) (Backup)
1	2666.3	**6**	2666.3
2	5374.8	**1**	804.7
2	5374.8	**7**	1531.5
3	3325.6	**2**	3325.6
4	2217.1	**3**	2217.1
5	1334.3	**4**	1334.3
6	4975	**5**	403.6
6	4975	**14**	1533
7	4247.6	**5**	403.6
7	4247.6	**13**	805.5
8	4973.2	**7**	1531.5
8	4973.2	**9**	403.2
9	1420.9	**10**	1420.9
10	2313.5	**11**	2313.5
11	3474.3	**12**	3474.3
12	5377	**13**	805.5
12	5377	**14**	1533
13	2475.7	**8**	2475.7
14	4246.4	**1**	804.7
14	4246.4	**9**	403.2

Table 2. The main characteristics of the 8-bus test system.

		***TDS* (sec)**		**I_P (A)**		***PTS* (A)**	
Relay	**CT Ratio**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
1	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
2	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
3	800 / 5	0.10	1.1	80.00	2.50	0.5	2.5
4	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
5	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
6	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
7	800 / 5	0.10	1.1	80.00	2.50	0.5	2.5
8	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
9	800 / 5	0.10	1.1	80.00	2.50	0.5	2.5
10	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
11	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
12	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
13	1200 / 5	0.10	1.1	120.00	2.50	0.5	2.5
14	800 / 5	0.10	1.1	80.00	2.50	0.5	2.5

4.2.1. CASE 3

Like CASE 1, this case is formulated as a NLP problem. The lower and upper bounds for TDS and I_P are given in Table 8. The BSA, DE, PSO, BH, EM, BBO and HS are run to solve this case and the results obtained after optimization are given in Table 9. The optimal operating times for primary and backup relays and *CTI* are given in Table 10 and they are represented in Figure 6. It can be seen from Table 9 that the proposed BSA gives the lowest operating time compared to the remaining methods.

Table 9. Obtained results for CASE 3.

Relay	Prop. BSA		DE		PSO		BH		EM		BBO		HS	
	TDS (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)
1	0.116	414.280	0.074	480.000	0.077	480.000	0.290	228.314	0.430	163.306	0.164	335.220	0.251	241.568
2	0.310	330.721	0.248	468.141	0.050	120.000	0.544	240.790	0.635	303.261	0.449	241.130	0.412	385.672
3	0.213	288.975	0.209	253.801	0.271	104.358	0.475	173.515	0.622	209.590	0.312	277.862	0.434	146.575
4	0.092	480.000	0.079	480.000	0.110	318.239	0.295	269.149	0.631	149.171	0.311	120.141	0.199	293.475
5	0.079	225.863	0.050	284.539	0.050	297.609	0.208	192.638	0.306	147.023	0.200	125.730	0.156	199.995
6	0.229	332.526	0.154	462.115	0.309	120.000	0.420	203.046	0.608	216.382	0.386	120.130	0.371	228.296
7	0.244	311.259	0.230	318.070	0.320	320.000	0.448	196.244	0.566	209.120	0.430	156.063	0.450	208.133
8	0.157	474.858	0.151	432.899	0.219	480.000	0.363	288.151	0.546	272.141	0.286	251.250	0.425	285.950
9	0.050	320.000	0.050	320.000	0.050	278.298	0.237	127.955	0.348	116.532	0.226	98.891	0.179	177.363
10	0.129	275.588	0.050	480.000	0.050	268.707	0.264	257.613	0.663	146.323	0.198	301.973	0.246	215.113
11	0.190	371.962	0.226	121.513	0.200	120.000	0.367	249.565	0.515	363.464	0.290	300.118	0.348	254.754
12	0.291	434.561	0.221	472.946	0.345	127.161	0.496	237.597	0.723	240.587	0.529	138.325	0.432	404.573
13	0.083	478.191	0.070	480.000	0.152	451.173	0.278	239.780	0.488	141.823	0.162	334.176	0.285	206.759
14	0.336	191.379	0.217	320.000	0.309	154.816	0.397	216.328	0.455	260.143	0.328	263.285	0.428	223.333
OF **(sec)**		**6.363**		**6.654**		**10.421**		**11.401**		**15.913**		**7.547**		**11.760**

Table 10. Operating times and *CTI* for CASE 3.

Primary Relay	Operating time (sec)	Backup Relay	Operating time (sec)	*CTI* (sec)
1	0.306	**6**	0.623	0.317
2	0.683	**1**	0.988	0.305
2	0.683	**7**	0.985	0.302
3	0.542	**2**	0.853	0.311
4	0.355	**3**	0.657	0.302
5	0.218	**4**	0.518	0.300
6	0.461	**5**	0.911	0.450
6	0.461	**14**	0.987	0.526
7	0.593	**5**	0.911	0.318
7	0.593	**13**	0.992	0.400
8	0.479	**7**	0.985	0.506
8	0.479	**9**	0.916	0.437
9	0.210	**10**	0.510	0.300
10	0.355	**11**	0.657	0.302
11	0.529	**12**	0.839	0.310
12	0.684	**13**	0.992	0.308
12	0.684	**14**	0.987	0.302
13	0.338	**8**	0.643	0.305
14	0.608	**1**	0.988	0.380
14	0.608	**9**	0.916	0.308

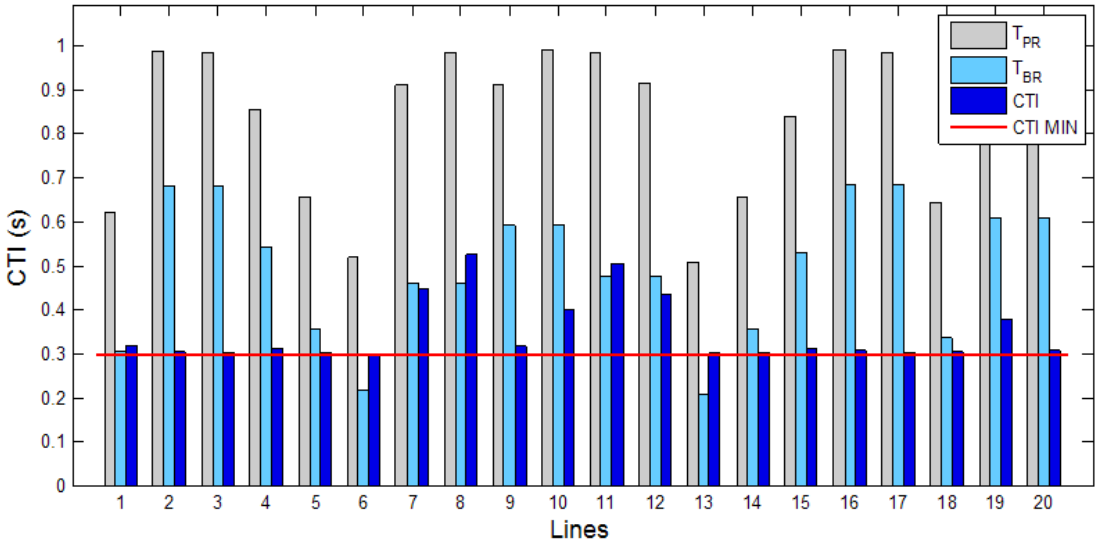

Figure 6. Operating times of primary and backup relays and *CTI* for CASE 3.

4.2.2. CASE 4

In this case, the DOCRs coordination problem is formulated as a MINLP problem. The lower and upper bounds for *TDS* and *PTS* are given in Table 8. The optimal results found using BSA, DE, PSO, BH, EM, BBO and HS are given in Table 11. Moreover, the operating times of primary and backup relays and *CTI* are given in Table 12 and represented graphically in Figure 7.

It can be seen that the reduction in the operating time with BSA ranges between 10.20 % and 56.03 % compared with the remaining methods. This confirms the superiority of the proposed BSA as it gives the minimum objective function value.

Table 11. Obtained results for CASE 4.

Relay	Prop. BSA		DE		PSO		BH		EM		BBO		HS	
	TDS (sec)	*PTS* (A)	*TDS* (sec)	*PTS* (A)	*TDS* (sec)	*PTS* (A)	*TDS* (sec)	*PTS* (A)	*TDS* (sec)	*PTS* (A)	*TDS* (sec)	*PTS* (A)	*TDS* (sec)	*PTS* (A)
1	0.258	0.750	0.086	2.000	0.127	2.000	0.284	1.250	0.432	0.750	0.222	1.000	0.325	0.750
2	0.295	2.000	0.281	1.750	0.255	0.500	0.620	1.250	0.653	1.500	0.403	1.000	0.472	1.000
3	0.269	1.250	0.224	1.750	0.122	0.500	0.599	1.250	0.647	1.500	0.400	0.500	0.360	1.250
4	0.139	1.000	0.161	0.750	0.050	1.000	0.442	1.000	0.434	1.000	0.187	0.750	0.178	1.500
5	0.050	1.250	0.050	1.250	0.076	1.250	0.350	0.500	0.258	0.500	0.083	1.000	0.173	0.750
6	0.245	2.000	0.225	1.500	0.817	0.500	0.568	1.000	0.542	1.000	0.371	0.750	0.399	1.250
7	0.282	1.750	0.281	1.750	0.050	2.000	0.591	1.000	0.724	0.750	0.293	1.750	0.426	1.250
8	0.204	1.500	0.324	0.500	0.050	2.000	0.538	1.250	0.515	1.250	0.416	0.750	0.352	1.000
9	0.050	2.000	0.050	2.000	0.050	2.000	0.335	0.750	0.373	0.500	0.295	0.500	0.134	1.250
10	0.100	1.750	0.196	0.500	0.050	1.750	0.517	1.000	0.399	1.000	0.367	0.500	0.187	1.250
11	0.174	2.000	0.329	0.500	0.449	0.500	0.586	1.250	0.493	1.000	0.314	1.500	0.328	1.000
12	0.267	2.000	0.305	1.750	0.598	0.500	0.523	1.000	0.608	1.250	0.387	1.750	0.424	1.250
13	0.101	1.750	0.086	2.000	0.377	0.500	0.416	0.750	0.436	0.750	0.291	0.750	0.196	1.500
14	0.259	2.000	0.373	1.000	0.450	1.750	0.444	1.500	0.547	1.250	0.500	0.750	0.367	1.750
***OF* (sec)**		**6.197**		**6.901**		**9.978**		**13.796**		**14.095**		**8.099**		**10.847**

Table 12. Operating times and *CTI* for CASE 4.

Primary Relay	Operating time (sec)	Backup Relay	Operating time (sec)	*CTI* (sec)
1	0.294	**6**	0.606	0.312
2	0.672	**1**	0.988	0.316
2	0.672	**7**	0.973	0.301
3	0.539	**2**	0.843	0.304
4	0.354	**3**	0.654	0.301
5	0.231	**4**	0.532	0.301
6	0.450	**5**	1.176	0.726
6	0.450	**14**	0.979	0.529
7	0.583	**5**	1.176	0.593
7	0.583	**13**	0.977	0.394
8	0.434	**7**	0.973	0.539
8	0.434	**9**	0.956	0.522
9	0.212	**10**	0.512	0.300
10	0.352	**11**	0.652	0.300
11	0.516	**12**	0.819	0.303
12	0.668	**13**	0.977	0.309
12	0.668	**14**	0.979	0.311
13	0.305	**8**	0.609	0.304
14	0.587	**1**	0.988	0.400
14	0.587	**9**	0.956	0.369

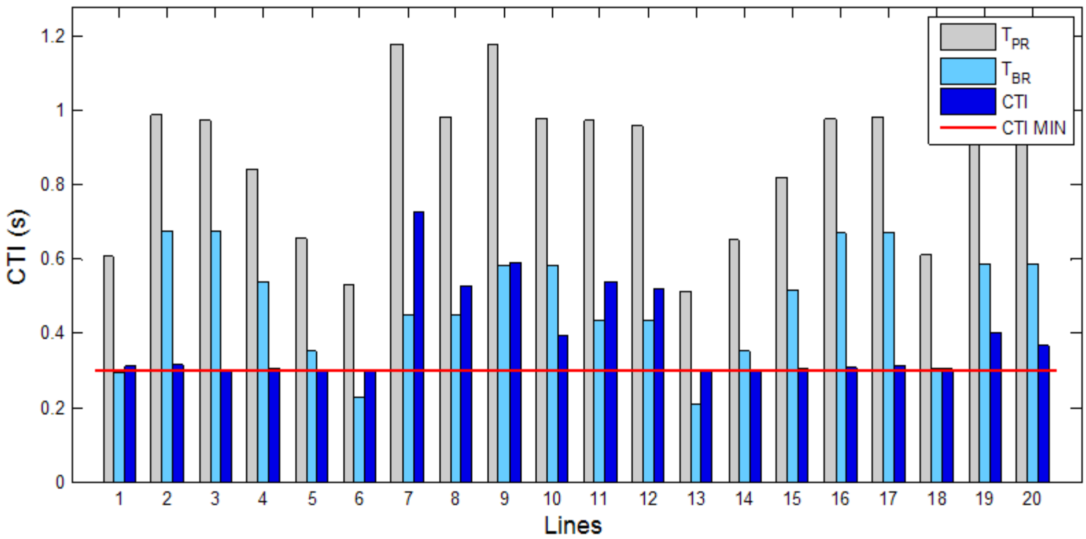

Figure 7. Operating times of primary and backup relays and *CTI* for CASE 4.

4.3. Test system 3: the 15-bus test system with DG

To demonstrate the scalability of the proposed BSA, a more complex system is investigated. This system is composed of 15 buses, 21 distribution lines, and 42 relays and it is a highly distributed generation (DG) penetrated distribution network as shown in Figure 8 [14]. The short-circuit currents measured by primary and backup relays are given in Table 13. A minimum *CTI* value of 0.2 is selected for this test system. Furthermore, this system has 84 design variables and 82 constraints.

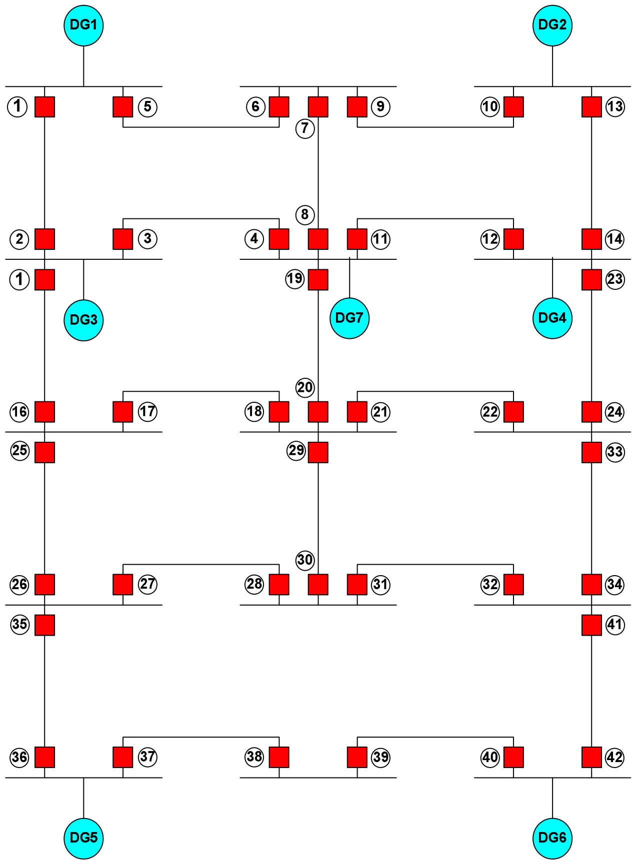

Figure 8. Single-line diagram of the 15-bus test system.

Table 13. Primary/backup relays fault currents for the 15-bus test system.

Primary Relay	I_F (A) (Primary)	Backup Relay	I_F (A) (Backup)	Primary Relay	I_F (A) (Primary)	Backup Relay	I_F (A) (Backup)
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**	797
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

Table 14. The main characteristics of the 15-bus test system.

		TDS **(sec)**		I_P **(A)**	
Relay	**CT Ratio**	**Min**	**Max**	**Min**	**Max**
1	800 / 5	0.10	1.10	80.00	400.00
2	1200 / 5	0.10	1.10	120.00	600.00
3	800 / 5	0.10	1.10	80.00	400.00
4	1200 / 5	0.10	1.10	120.00	600.00
5	800 / 5	0.10	1.10	80.00	400.00
6	600 / 5	0.10	1.10	60.00	300.00
7	600 / 5	0.10	1.10	60.00	300.00
8	1200 / 5	0.10	1.10	120.00	600.00
9	600 / 5	0.10	1.10	60.00	300.00
10	800 / 5	0.10	1.10	80.00	400.00
11	1200 / 5	0.10	1.10	120.00	600.00
12	1200 / 5	0.10	1.10	120.00	600.00
13	800 / 5	0.10	1.10	80.00	400.00
14	1200 / 5	0.10	1.10	120.00	600.00
15	1200 / 5	0.10	1.10	120.00	600.00
16	600 / 5	0.10	1.10	60.00	300.00
17	400 / 5	0.10	1.10	40.00	200.00
18	1600 / 5	0.10	1.10	160.00	800.00
19	800 / 5	0.10	1.10	80.00	400.00
20	1600 / 5	0.10	1.10	160.00	800.00
21	1600 / 5	0.10	1.10	160.00	800.00
22	400 / 5	0.10	1.10	40.00	200.00
23	1200 / 5	0.10	1.10	120.00	600.00
24	600 / 5	0.10	1.10	60.00	300.00
25	600 / 5	0.10	1.10	60.00	300.00
26	600 / 5	0.10	1.10	60.00	300.00
27	600 / 5	0.10	1.10	60.00	300.00
28	600 / 5	0.10	1.10	60.00	300.00
29	1600 / 5	0.10	1.10	160.00	800.00
30	400 / 5	0.10	1.10	40.00	200.00
31	600 / 5	0.10	1.10	60.00	300.00
32	600 / 5	0.10	1.10	60.00	300.00
33	600 / 5	0.10	1.10	60.00	300.00
34	400 / 5	0.10	1.10	40.00	200.00
35	600 / 5	0.10	1.10	60.00	300.00
36	800 / 5	0.10	1.10	80.00	400.00
37	800 / 5	0.10	1.10	80.00	400.00
38	400 / 5	0.10	1.10	40.00	200.00
39	400 / 5	0.10	1.10	40.00	200.00
40	800 / 5	0.10	1.10	80.00	400.00
41	400 / 5	0.10	1.10	40.00	200.00
42	800 / 5	0.10	1.10	80.00	400.00

4.3.1. CASE 5

This case is formulated as a NLP problem. The lower and upper bounds used for the optimization are given in Table 14. The optimal results found are given in Table 15.

Table 15. Obtained results for CASE 5.

	BSA		DE		PSO		BH		EM		BBO		HS	
Relay	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)	*TDS* (sec)	I_P (A)
1	0.266	81.399	0.257	80.020	0.195	227.097	0.333	216.193	0.604	80.083	0.120	263.407	0.309	174.572
2	0.212	150.800	0.229	120.007	0.304	247.584	0.299	240.380	0.538	120.063	0.087	362.359	0.233	275.509
3	0.321	80.145	0.255	80.222	0.317	259.895	0.435	230.236	0.611	80.071	0.289	82.819	0.433	148.192
4	0.229	120.000	0.232	121.555	0.158	523.203	0.341	339.961	0.548	120.061	0.196	121.528	0.169	288.024
5	0.292	109.010	0.276	80.098	0.405	345.157	0.377	216.585	0.544	80.090	0.157	294.025	0.414	117.678
6	0.299	61.496	0.296	64.952	0.243	216.170	0.392	164.734	0.594	60.084	0.228	60.018	0.279	156.987
7	0.308	60.011	0.133	300.000	0.419	160.856	0.449	136.286	0.533	60.086	0.215	129.917	0.348	165.748
8	0.299	120.002	0.116	594.778	0.384	208.561	0.377	369.559	0.589	120.062	0.144	313.501	0.221	180.675
9	0.332	62.833	0.100	150.711	0.371	179.571	0.387	133.608	0.586	60.097	0.159	223.645	0.275	194.251
10	0.309	80.000	0.196	179.328	0.462	167.023	0.482	184.040	0.570	80.070	0.267	80.402	0.354	223.016
11	0.247	120.000	0.191	147.009	0.551	120.000	0.367	280.597	0.531	120.062	0.149	328.028	0.340	176.513
12	0.285	120.000	0.082	599.965	0.585	120.000	0.323	297.978	0.565	120.060	0.230	147.856	0.217	281.262
13	0.328	80.058	0.050	400.000	0.629	108.307	0.416	190.668	0.555	80.081	0.289	80.314	0.288	341.922
14	0.223	156.457	0.076	578.395	0.325	198.646	0.340	294.734	0.565	120.061	0.142	275.221	0.292	236.098
15	0.157	245.062	0.228	120.000	0.321	231.255	0.342	275.370	0.546	120.062	0.136	297.579	0.266	225.086
16	0.280	60.094	0.085	300.000	0.230	131.194	0.376	178.416	0.590	60.080	0.172	140.235	0.287	64.924
17	0.241	53.970	0.187	40.000	0.371	40.000	0.369	91.245	0.549	40.071	0.204	80.210	0.341	44.598
18	0.252	160.407	0.202	160.000	0.424	189.162	0.263	407.298	0.576	160.190	0.107	520.547	0.346	353.934
19	0.286	80.001	0.231	80.000	0.428	250.919	0.370	200.839	0.575	80.083	0.255	115.718	0.254	220.331
20	0.274	160.111	0.076	800.000	0.332	308.112	0.403	389.187	0.557	160.190	0.125	424.560	0.436	187.135
21	0.242	192.923	0.050	797.761	0.311	378.004	0.331	394.340	0.547	160.190	0.077	711.210	0.235	480.000
22	0.286	40.140	0.092	199.931	0.391	60.883	0.426	108.357	0.570	40.050	0.229	69.436	0.304	68.006
23	0.210	185.887	0.183	120.000	0.239	204.688	0.314	308.935	0.580	120.063	0.261	120.892	0.256	299.814
24	0.242	84.986	0.093	222.312	0.248	239.124	0.406	164.126	0.555	60.152	0.191	106.878	0.287	90.501
25	0.280	83.603	0.245	60.041	0.579	60.000	0.366	150.617	0.609	60.076	0.314	65.161	0.317	159.975
26	0.297	60.402	0.179	98.346	0.222	60.000	0.399	156.572	0.570	60.116	0.258	60.508	0.287	148.222
27	0.275	75.984	0.111	300.000	0.288	241.402	0.368	149.212	0.581	60.080	0.271	76.475	0.322	125.862
28	0.329	80.743	0.124	296.945	0.313	231.716	0.406	157.815	0.602	60.067	0.270	121.590	0.393	76.707
29	0.246	260.245	0.096	721.553	0.162	671.877	0.421	389.271	0.597	160.190	0.284	163.835	0.275	624.099
30	0.288	40.011	0.106	196.554	0.333	200.000	0.344	98.454	0.558	40.058	0.205	41.071	0.417	127.406
31	0.253	100.061	0.050	299.983	0.404	60.000	0.363	156.276	0.565	61.220	0.190	175.627	0.298	245.960
32	0.265	81.557	0.078	295.692	0.471	60.003	0.407	160.477	0.531	60.061	0.170	162.875	0.325	185.837
33	0.336	72.588	0.122	279.466	0.219	300.000	0.400	156.324	0.592	60.068	0.311	88.048	0.277	272.950
34	0.342	40.000	0.109	199.040	0.414	52.245	0.452	96.897	0.580	40.090	0.170	167.569	0.311	116.692
35	0.266	98.925	0.115	299.998	0.500	100.804	0.453	142.617	0.573	60.083	0.318	60.922	0.252	251.166
36	0.263	113.877	0.244	80.001	0.385	150.976	0.424	179.341	0.566	80.082	0.188	203.495	0.380	109.474
37	0.302	117.565	0.199	202.381	0.784	80.000	0.456	215.665	0.596	80.075	0.295	80.347	0.248	217.818
38	0.340	40.238	0.293	40.422	0.312	134.518	0.377	125.416	0.561	40.061	0.305	40.088	0.368	85.566
39	0.325	42.728	0.131	175.739	0.149	142.181	0.502	110.299	0.588	40.067	0.261	40.026	0.131	110.477
40	0.326	103.831	0.156	339.280	0.271	251.527	0.367	220.169	0.556	80.085	0.329	80.914	0.333	194.373
41	0.299	70.518	0.130	199.967	0.050	120.266	0.432	104.663	0.574	40.069	0.359	40.079	0.247	119.954
42	0.286	82.845	0.195	80.000	0.225	216.264	0.330	177.652	0.568	80.076	0.127	259.590	0.259	233.548
OF **(sec)**	**16.293**		**17.206**		**41.460**		**35.443**		**43.157**		**16.580**		**108.794**	

From Table 15 it appears that the BSA outperforms by far the remaining methods. It can be observed that the operating time with BSA is greatly reduced compared to that of other methods. This shows the scalability of the BSA to large-scale DOCRs coordination problems.

Table 16. Operating times and *CTI* for CASE 5.

Primary Relay	Operating time (sec)	Backup Relay	Operating time (sec)	*CTI* (sec)	Primary Relay	Operating time (sec)	Backup Relay	Operating time (sec)	*CTI* (sec)
1	0.333	**6**	0.543	0.210	**20**	0.312	**30**	0.520	0.209
2	0.221	**4**	0.455	0.234	**21**	0.286	**17**	0.517	0.231
2	0.221	**16**	0.599	0.378	**21**	0.286	**19**	0.497	0.210
3	0.396	**1**	0.597	0.202	**21**	0.286	**30**	0.520	0.234
3	0.396	**16**	0.599	0.203	**22**	0.324	**23**	0.764	0.440
4	0.302	**7**	0.600	0.298	**22**	0.324	**34**	0.531	0.206
4	0.302	**12**	0.557	0.256	**23**	0.414	**11**	0.624	0.211
4	0.302	**20**	0.599	0.298	**23**	0.414	**13**	0.621	0.207
5	0.423	**2**	0.631	0.208	**24**	0.307	**21**	0.761	0.454
6	0.391	**8**	0.594	0.203	**24**	0.307	**34**	0.531	0.223
6	0.391	**10**	0.635	0.244	**25**	0.449	**15**	0.659	0.210
7	0.432	**5**	0.643	0.211	**25**	0.449	**18**	0.658	0.210
7	0.432	**10**	0.635	0.202	**26**	0.404	**28**	0.638	0.233
8	0.354	**3**	0.599	0.245	**26**	0.404	**36**	0.697	0.292
8	0.354	**12**	0.557	0.203	**27**	0.487	**25**	0.709	0.223
8	0.354	**20**	0.599	0.246	**27**	0.487	**36**	0.697	0.210
9	0.377	**5**	0.643	0.266	**28**	0.446	**29**	0.652	0.206
9	0.377	**8**	0.594	0.217	**28**	0.446	**32**	0.653	0.207
10	0.421	**14**	0.623	0.202	**29**	0.286	**17**	0.517	0.231
11	0.399	**3**	0.599	0.200	**29**	0.286	**19**	0.497	0.211
11	0.399	**7**	0.600	0.201	**29**	0.286	**22**	0.517	0.231
11	0.399	**20**	0.599	0.201	**30**	0.365	**27**	0.634	0.268
12	0.299	**13**	0.504	0.205	**30**	0.365	**32**	0.653	0.288
12	0.299	**24**	0.511	0.212	**31**	0.428	**27**	0.634	0.206
13	0.351	**9**	0.552	0.200	**31**	0.428	**29**	0.652	0.224
14	0.280	**11**	0.624	0.344	**32**	0.362	**33**	0.731	0.369
14	0.280	**24**	0.511	0.230	**32**	0.362	**42**	0.622	0.260
15	0.253	**1**	0.597	0.344	**33**	0.561	**21**	0.761	0.200
15	0.253	**4**	0.455	0.202	**33**	0.561	**23**	0.764	0.203
16	0.398	**18**	0.658	0.261	**34**	0.410	**31**	0.736	0.325
16	0.398	**26**	0.604	0.207	**34**	0.410	**42**	0.622	0.212
17	0.360	**15**	0.659	0.299	**35**	0.424	**25**	0.709	0.285
17	0.360	**26**	0.604	0.244	**35**	0.424	**28**	0.638	0.214
18	0.250	**19**	0.497	0.247	**36**	0.488	**38**	0.702	0.214
18	0.250	**22**	0.517	0.267	**37**	0.444	**35**	0.646	0.203
18	0.250	**30**	0.520	0.271	**38**	0.591	**40**	0.793	0.203
19	0.318	**3**	0.599	0.281	**39**	0.463	**37**	0.667	0.205
19	0.318	**7**	0.600	0.281	**40**	0.592	**41**	0.800	0.208
19	0.318	**12**	0.557	0.239	**41**	0.517	**31**	0.736	0.218
20	0.312	**17**	0.517	0.206	**41**	0.517	**33**	0.731	0.214
20	0.312	**22**	0.517	0.205	**42**	0.375	**39**	0.578	0.203

4.4. Performance evaluation study

In this paper, five cases have been investigated. For each case, 30 trial runs have been executed using BSA, DE, PSO, BH, EM, BBO and HS and the best results have been reported as given above. In this section, an extensive evaluation study has been done in order to make reliable conclusions about the overall performance of the proposed BSA.

The ranking procedure developed in this paper is explained below. Ranking is given to each method on every case based on the following criteria:

- Cases: 5 cases are presented in this paper,

- Runs/case: 30 runs per case are done,
- Comparison: Comparison of methods have been done based on the 'Best' values obtained using the average rank calculated using the following formula:

$$Average\ \ Rank = \frac{Total\ \ Rank}{5} \tag{14}$$

Table 17 shows the normalized operating time with respect to that of the proposed BSA for the five cases considered. It can be seen that all the normalized times of other techniques are higher than that of the proposed BSA. This demonstrates the effectiveness of the proposed BSA to solve the DOCRs coordination problem.

In Table 18, the final rankings are calculated and the final ranking of each method is given. From Table 18 it can be noticed that the BSA outperforms the other optimization methods considered in this study for solving the DOCRs coordination problem.

Table 17. The normalized operating time for all cases.

	BSA	**DE**	**PSO**	**BH**	**EM**	**BBO**	**HS**
CASE 1	1.00	1.00	1.01	2.14	1.88	1.03	1.13
CASE 2	1.00	1.00	1.04	2.00	1.32	1.07	1.09
CASE 3	1.00	1.05	1.64	1.79	2.50	1.19	1.85
CASE 4	1.00	1.11	1.61	2.23	2.27	1.31	1.75
CASE 5	1.00	1.06	2.54	2.18	2.65	1.02	6.68

Table 18. Comparison of methods and final ranking.

	BSA	**DE**	**PSO**	**BH**	**EM**	**BBO**	**HS**
CASE 1	2	1	3	7	6	4	5
CASE 2	1	1	3	7	6	4	5
CASE 3	1	2	4	5	7	3	6
CASE 4	1	2	4	6	7	3	5
CASE 5	1	3	5	4	6	2	7
Total Rank	6	9	19	29	32	16	28
Average Rank	1.2	1.8	3.8	5.8	6.4	3.2	5.6
Final Ranking	**1st**	**2nd**	**4th**	**6th**	**7th**	**3rd**	**5th**

5. Conclusion

In this work, backtracking search algorithm is proposed for solving the directional overcurrent relays coordination problem. The DOCRs coordination problem has been formulated as a nonlinear programming problem and as a mixed integer nonlinear programming problem. The proposed BSA-based approach has been developed and employed with the aim of minimizing the operating time of all primary protection relays. In order to evaluate the performance of the proposed technique it has been applied to three test systems with different complexities. The obtained results demonstrate that the proposed technique is an efficient and reliable tool for the coordination of directional overcurrent relays. Moreover, the results confirm the superiority of the proposed BSA over some well-known optimization techniques considered in this study.

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