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Hybrid Algorithm combining Lambda Iteration and Bee Colony Optimization to Solve an Economic Dispatch Problem with Prohibited Operating Zones

***Abstract**. This research aimed to solve an economic dispatch problem with prohibited operating zones using a hybrid method combining lambda iteration and bee colony optimization with smooth cost function characteristics. The constraints of economic dispatch consisted of load demand, transmission loss, ramp rate limits and prohibited operating zones. To verify the performance of the proposed algorithm, it was operated using a simulation of the MATLAB program and tested with two case studies with certain operating zones involving either three or six generators. The study found that the proposed method could provide better solutions than the others that were tested in terms of a quality solution, and computational and convergence efficiently. It can be concluded that the proposed method was effective in solving the issue of economic dispatch.*

Streszczenie.** W aertykule przedstawiono algorytmy umożliwiające optymalizację ekonomicznego rozsyłu energii. Uwzględniono wzbronione zkakresy mocy wyjściowej.* ***Hybrydowy algorytm wykorzystujący iteracje Lambda i optymalizację rojową do rozwiązywania problemu ekonomicznego rozsyłu enmergii z wzbronionymi zakresami mocy.

Keywords: Bee Colony Optimization, Lambda Iteration, Economic Dispatch.
Słowa kluczowe: ekonomiczny rozsył energii, iteracja Lambda, algorytmy rojowe.

Introduction

Reliability, stability, and economic efficiency are very important for the planning and operation of a power generation system. To get profits from the capital invested, efficient economic operation is critical. Operational economics, involving then minimization of power generation and delivery costs, is called Economic Dispatch (ED). The objective of economic dispatch is to minimize the total cost of all generations while satisfying all operating constraints.

To solve the problem of economic dispatch, there are two approaches, including classical and meta-heuristic methods. Classical methods, such as lambda iteration and gradient methods are the most common ones applied to solve the continuous ED problem [1]-[2]. These methods require incremental fuel cost curves which are piecewise and linear. Lagrangian relaxation [3] and dynamic programming [4] is one of the approaches that are used to solve a non-linear and discontinuous ED problem. Numerical methods can cause problems in complicated and large power systems as they suffer from the complexities of dimensionality and local optimality. Recently, meta-heuristic methods have been used to solve the economic dispatch problem. Such methods include simulated annealing (SA) [5]-[6], a genetic algorithm (GA) [7]-[8], an evolutionary program (EP) [9]-[10], tabu search (TS) [11], particle swarm optimization (PSO) [12]-[14], ant colony optimization (ACO) [15]-[17] and bee colony optimization (BCO) [18]-[20]. These methods can obtain a global optimum within a short time and guarantee an optimum solution. However, in these techniques the initial populations are generated randomly. This results in long computation times and a long time to convergence when the generated initial populations are too far from the optimum solution. This problem has been solved by HLBCO [21]-[22] in which the initial population of BCO is modified. However, this method considers a static economic dispatch situation and presents a fundamental constraint to the economic dispatch problem. In this paper, a hybrid algorithm combining lambda iteration with BCO is proposed to solve both static and dynamic economic dispatches. The proposed method focuses on minimizing the total fuel cost of all electrical power generation units while satisfying the technical constraints of power balance, ramp rate limits and prohibited operating zones. The feasibility of the proposed method is demonstrated using two case studies with either three generators operating under static economic dispatch or six generators under dynamic economic dispatch conditions. The results from previously published methods are compared with the proposed method.

This paper is organized as follows: Section II expresses the problem formulation of the economic dispatches. Section III explains the Hybrid algorithm of lambda iteration and bee colony optimization (HLIBCO) for solving economic dispatches. Section IV shows the case studies. The simulation results are shown in Section V and the last section concludes the paper.

Economic Dispatch Problem Formulation

In a power system, the unit commitment problem has various sub-problems varying from linear programming problems to complex non-linear problems. The concerned problem, i.e., ED problem is one of the non-linear programming sub-problems of unit commitment. It is about minimizing the fuel cost of generating units for a specific period of operation so as to accomplish optimal generation dispatch among operating units and in return satisfying the system load demand, generator operation constraints with ramp rate limits and prohibited operating zones.

Objective functions

The objective function corresponding to production cost can be approximated to be a quadratic function of the active power outputs from the committed generating units. Symbolically, it is represented as follows:

$$\text{(1)} \qquad Minimize: \mathrm{F}_T = \sum_{i=1}^{N} F_i(P_i)$$

where F_T is the total generation cost, N is the number of generators committed to the operating system and F_i is the generation cost function of i^{th} generator is usually expressed as a quadratic polynomial as follows:

$$\text{(2)} \qquad F_i(P_i) = a_i P_i^2 + b_i P_i + c_i$$

where a_i, b_i and c_i are the cost coefficients of the i^{th} generator; P_i is the power output of the i^{th} generator.

Constrain

The objective functions are subject to the following constraints.

Power balance constraint

This is represented as being all of the load capacity and is equal to the sum of the total amount of electricity demand with a total power loss in the transmission system, as follows:

$$\sum_{i=1}^{N}(P_i) = P_D + P_{loss} \tag{3}$$

where P_D is the load demand and P_{loss} is the total transmission network losses, which is a function of the unit power outputs that can be represented using B coefficients as follows:

$$P_{loss} = \sum_{i=1}^{N}\sum_{j=1}^{N} P_i B_{ij} P_j + \sum_{j=1}^{N} B_{0i} P_i + B_{00} \tag{4}$$

Generation limits constraint

The power output of each generating unit has to lie in between a lower and an upper bound. This is represented by a pair of side constraints as follows:

$$P_i^{\min} \le P_i \le P_i^{\max} \tag{5}$$

where, $P_{i,min}$ and $P_{i,max}$ are respectively the lower and upper bounds for power outputs of the i^{th} generating unit.

Ramp-rate limits

One of unpractical assumption that prevailed for simplifying the problem in many of the earlier research is that the adjustments of the power outputs are unbounded. However, under practical circumstances ramp rate limit restricts the operating range of all the online units for adjusting the generator operation between two operating periods. The generation may increase or decrease with corresponding upper and downward ramp rate limits. So, units are constrained due to these ramp rate limits as mentioned below (6)-(7):

$$P_i^o - P_i \le UR_i \tag{6}$$

$$P_i^o - P_i \ge DR_i \tag{7}$$

where, P_i^o is the power output that the generation unit generated in the previous step, DR_i and UR_i are the upper and lower limits of the prohibited operating zone of i^{th} generators. The rating of the i^{th} generator is computed as follows:

$$\max(P_i^{\min}, P_i^0 - DR_i) \le Pi \le \min(P_i^{\max}, P_i^0 + UR_i) \tag{8}$$

Prohibited Operating Zone

The input–output curve of prohibited operating zones in real generating unit that the prohibited operating zones happen due to some vibration phenomena on the shaft. The prohibited operating zone has discontinuous input–output characteristics as shown in Fig. 1.

In the actual operation, adjusting the generation output P_i of a unit must avoid working in the prohibited operating zones. The feasible operating zones of unit can be described as follows:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i P_i = \begin{cases} P_i^{\min} \le P_i \le P_{i,1}^l \\ P_{i,j-1}^u \le P_i \le P_{i,j}^l \\ P_{i,n}^u \le P_i \le P_{i,1}^{\max} \end{cases}, \; j = 2,3 \ldots n_i \tag{9}$$

where, n_i is the number of prohibited zones of i^{th} generator. $P^l_{i,j}$, $P^u_{i,j}$ are the lower and upper power output of prohibited zones j of i^{th} generator, respectively.

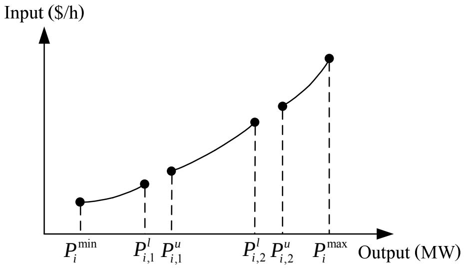

Fig. 1. Prohibited operating zone function cost curve.

Hybrid of Lambda Iteration and Bee Colony Optimization (HLIBCO)

The BCO algorithm has an advantage in that it provides global optimal solutions and it has the capability to solve difficult combinatorial optimization problems. BCO algorithm was proposed by Karaboga for numerical optimization [23]. This algorithm mimics the food foraging behavior of honey bees. The colony of bees consists of two groups, scout and employed bees. The scout bees seek a new food source and the employed bees look for a food source within the neighborhood of the food source in their memories. It has the advantage in providing the global optimal solutions and has the capability for solving combinatorial optimization problems. However, in this algorithm, the initial populations are generated randomly causing in long computation times and a long time to convergence when the generated initial populations are too far from the optimum solution.

To avoid these problems, the Lambda iteration is used for determining the initial value for BCO algorithm. This technique called the hybrid of Lambda iteration and Bee colony optimization (HLIBCO) is used to solve the economic dispatch problem with prohibited operating zones. Fig. 2 shows the flowchart of the HLIBCO algorithm for solving the dynamic economic dispatch problem and is described as follows:

Step 1: Specify the parameters of the HLIBCO as shown in Table 1. These parameters were found by trial and error. Where, the values of *N*, *S*, *E*, *NE* and *NO* were adjusted between 10 to 100, 5 to 90, 3 to 80, 10 to 100 and 10 to 100, respectively. This processing gives the optimal parameters as shown in Table 1 that result the best answer and minimum number of iteration.

Step 2: Calculate the value of λ for initial configuration of the system for the scout bees. In this process, the initial value of λ is determined as follows:

$$\lambda = \frac{P_D + \sum_{i=1}^{m} \frac{b_i}{c_i}}{\sum_{i=1}^{m} \frac{1}{c_i}} \tag{10}$$

Table 1. The parameters used within BCO and HLIBCO

Parameters	Number
Population size (*N*)	20
Number of selected sites (*S*)	10
Number of best sites (*E*)	5
Number of bees around best sites (*NE*)	50
Number of bees around other sites (*NO*)	50

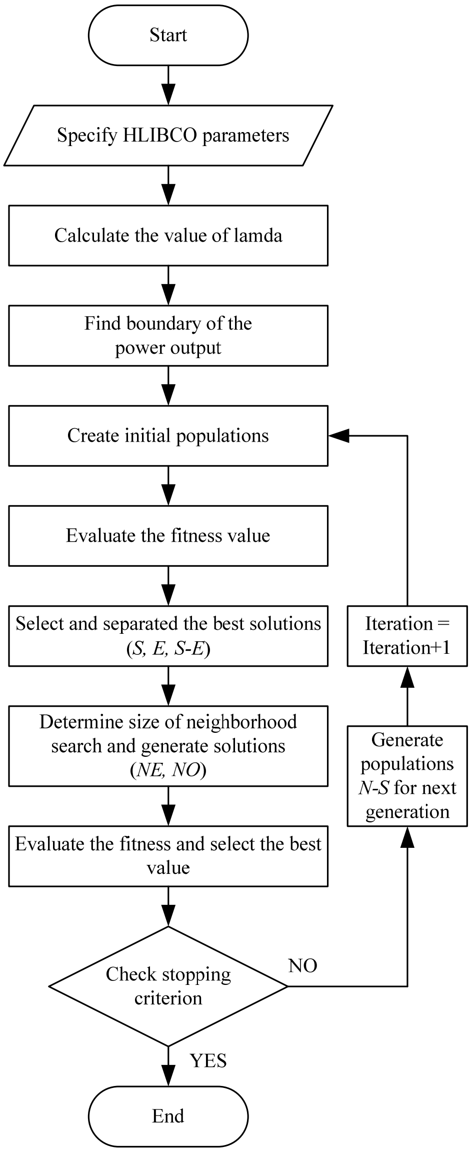

Fig. 2. Proposed HLIBCO algorithm.

Step 3: Find the lower and upper limits of the i^{th} generating unit using the following:

$$P_i^{\max} = \frac{\lambda - b_i}{c_i} + \left(\frac{\lambda - b_i}{c_i} \times rank \right) \tag{11}$$

$$P_i^{\min} = \frac{\lambda - b_i}{c_i} - \left(\frac{\lambda - b_i}{c_i} \times rank \right) \tag{12}$$

where b_i and c_i are the cost coefficients of the i^{th} generator and *rank* is the number between 0-1 used for determining the boundary of solution.

Step 4: Generate randomly the initial populations (*N)* of the power output of the i^{th} generation from step 3 can be expressed as follows:

$$P_i = P_i^{\min} + ((P_i^{\max} - P_i^{\min}) \times rand(1)) \tag{13}$$

Step 5: Send scout bees to find the solution of the value from step 4 and evaluate the fitness value of the initial populations.

Step 6: Choose a good value (*S*) and are divide into two groups, best value (*E*) and available value (*S-E*).

Step 7: Send employed bees around for best value (*NE*) and around other value (*NO*)

Step 8: Evaluate the fitness value of each. Then, select the best solution from each patch.

Step 9: Check stopping criterion. If conditions that are set are met, then show the most appropriate solution; otherwise, generate populations *N-S* for next generation, iteration = Iteration+1 and back to step 4.

Case studies

To verify the effectiveness of the proposed HLIBCO algorithm, it was applied to solve the economic dispatch problem with prohibited operating zones in two different test cases. These were a three unit system and a six unit system. Each optimization method was implemented in an MATLAB program which ran on a 2.30 GHz Intel (R) Core (TM) i5 with 8 GB of RAM.

The first case study

The system consisted of a three unit system and a 300 MW load demand. The system data are as shown in Tables 2 and 3. The system loss coefficient matrix following [24].

The results of the proposed methods are compared with the two-phase neural network (2PNN), particle swarm optimization (PSO) and hybrid particle swarm optimization (HPSO) methods.

$$B_{ij} = \begin{bmatrix} 0.000136 & 0.0000175 & 0.000184 \\ 0.0000175 & 0.000154 & 0.000283 \\ 0.000184 & 0.000283 & 0.00161 \end{bmatrix}$$

Table 2 generator data for case 1

Unit	a_i	b_i	c_i	P_i^{min}	P_i^{max}
1	0.00525	8.663	328.13	50	250
2	0.00609	10.04	136.91	5	150
3	0.00592	9.76	59.16	15	100

Table 3 ramp rate limits and prohibited zone for case 1

Unit	P_i^o	UR_i	DR_i	Prohibited zone	
				Zone 1	Zone 2
1	215	55	95	[105-117]	[165-177]
2	72	55	78	[50-60]	[92-102]
3	98	45	64	[25-32]	[60-67]

The second case study

The test system for this case consisted of 6 units, 26 buses and 46 transmission lines which included the generation limits, fuel cost coefficients, ramp-rate limits and prohibited operating zones. The transmission loss was calculated using a B matrix following [25].

$$B_{ij} = 10^{-1} \begin{bmatrix} 0.017 & 0.012 & 0.007 & -0.001 & -0.005 & -0.002 \\ 0.012 & 0.014 & 0.009 & 0.001 & -0.006 & -0.001 \\ 0.007 & 0.009 & 0.031 & 0.0 & -0.010 & -0.006 \\ -0.001 & 0.001 & 0.0 & 0.24 & -0.006 & -0.008 \\ -0.005 & -0.006 & -0.010 & -0.006 & 0.129 & -0.002 \\ -0.002 & -0.001 & -0.006 & -0.008 & -0.002 & 0.15 \end{bmatrix}$$

$$B_{0i} = 10^{-3} \times \begin{bmatrix} -0.3908 & -0.1297 & 0.7047 & 0.0591 & 0.2161 & -0.6635 \end{bmatrix}$$

$$B_{00} = 0.056$$

A one day scheduling period was divided into 24 intervals and the min-max load demand in the scheduling period was 930 MW and 1263 MW, respectively. The characteristics of the six thermal units are given in Tables 4 and 5 [25].

Table 4 generator data for case 2

Unit	a_i	b_i	c_i	P_i^{min}	P_i^{max}
1	0.0070	7.00	240	100	500
2	0.0095	10.0	200	50	200
3	0.0090	8.50	220	80	300
4	0.0090	11.0	200	50	150
5	0.0080	10.5	220	50	200
6	0.0075	12.0	190	50	120

Table 5 Ramp rate limits and prohibited zone for case 2

Unit	P_i^o	UR_i	DR_i	Prohibited zone	
				Zone 1	Zone 2
1	340	80	120	[210-240]	[350-380]
2	134	50	90	[90-110]	[140-160]
3	240	65	100	[150-170]	[210-240]
4	90	50	90	[80-90]	[110-120]
5	110	50	90	[90-110]	[140-150]
6	52	50	90	[75-85]	[100-105]

Simulation and results

To validate the performance of the algorithm, this paper takes example for two test cases and tests the performance of the HLIBCO is used to solve both static (case 1) and dynamic (case 2) economic dispatches is proposed.

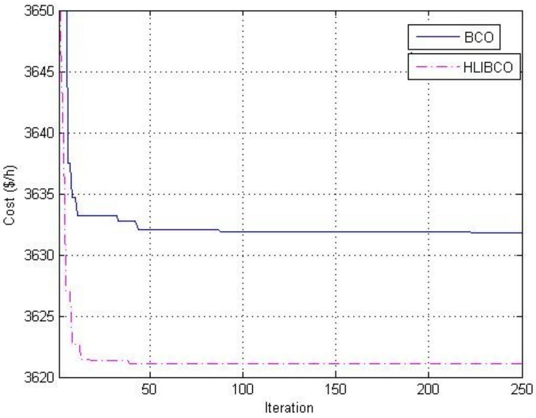

Fig. 3. Solution and convergence time of BCO and HLIBCO for case 1

The results of first case study

The results obtained for this case study using the proposed HLIBCO, BCO, 2PNN, PSO and HPSO methods are given in Tables 6-7 and Fig. 3. From these comparisons it was found that the result obtained by the HLIBCO algorithm had fast convergence, less computation time, less transmission loss and less total generation cost when it was compared with the BCO algorithm. Similarly, the cost function achieved by the HLIBCO was significantly better than those obtained by the 2PNN, PSO and HPSO methods (Table 7). In comparison of the power output of the three units the output of P_3 is almost the same for the four methods and the outputs of P_1 and P_2 are different for the four methods. Since random algorithms start with P_1-P_3, respectively, when P_1 and P_2 randomly satisfy the conditions, the value of P_3 is nearly the same, and P_1 and P_2 are different.

Table 6 Results of BCO and HLIBCO

Unit Output	BCO	HLIBCO
P1 (MW)	205.96	199.24
P2 (MW)	72.62	77.53
P3 (MW)	34.00	34.04
TP (MW)	312.58	310.81
Total cost ($/h)	3631.06	3621.01
Power Loss	12.58	10.81

Table 7 Results of three units system

Unit Output	2PNN [24]	PSO [25]	HPSO [26]	HLIBCO
P1 (MW)	165	190.50	200.18	199.24
P2 (MW)	113.4	85.77	76.26	77.53
P3 (MW)	34.05	34.8	34.40	34.04
TP (MW)	312.45	311.16	310.84	310.81
Total cost($/h)	3652.60	3631.1	3623.11	3621.01
Power Loss	12.45	11.16	10.84	10.81

The results of second case study

The simulation results for the appropriate values from the BCO and HLIBCO methods are shown in Tables 8-9 and Fig. 4-7. Table 8 illustrates the convergence characteristics obtained with the BCO method. The number of iterations were 330 and 490 and total generation costs are 313,388 $/day. In the HLIBCO method there were 124 and 188 iterations and total generation costs were 313,360.47 $/day (Table 9). It was found that the results obtained by the HLIBCO algorithm were better than those from the BCO method in terms of computational time, convergence time and total generation costs. Table 10 illustrates the results of the proposed algorithm in comparison with the λ-iteration, BM, SAMF and BCO methods, where the proposed method demonstrates its effectiveness in terms of minimizing generating costs and transmission loss.

Fig. 4-7. Show the convergence time of BCO and HLIBCO for first 4 hours predicted power demands. From these comparisons it was found that the result obtained by the HLIBCO algorithm had fast convergence, less computation time, less transmission loss and less total generation cost when it was compared with the BCO algorithm.

Table 8 The optimal dispatches six units system of BCO

t/U	1	2	3	4	5	6	P_D	P_L	Iteration	Fuel cost
1	388.25	123.91	207.31	79.48	113.13	50.23	955	7.31	425	11419.9719
2	381.39	121.77	207.13	76.64	111.25	50.97	942	7.15	403	11257.3870
3	382.42	119.05	200.64	76.01	113.73	50.16	935	7.01	444	11170.0408
4	380.67	115.40	201.63	77.19	111.68	50.35	930	6.91	480	11107.5824
5	382.42	119.05	200.64	76.01	113.73	50.16	935	7.01	444	11170.0408
6	385.99	128.41	203.60	90.90	111.04	50.28	963	7.22	458	11520.4990
7	388.80	160.18	204.58	72.73	115.99	54.56	989	7.85	424	11861.2545
8	401.75	138.17	209.95	100.14	125.26	55.82	1023	8.09	427	12282.1841
9	420.78	160.44	241.34	109.95	136.24	67.13	1126	9.88	426	13616.1122
10	421.76	160.96	242.35	127.69	136.51	70.77	1150	10.03	442	13933.3308
11	438.63	164.34	250.96	129.48	154.59	74.29	1201	11.09	468	14607.4256
12	444.28	168.85	253.61	132.72	157.96	89.17	1235	11.59	471	15061.9502
13	430.90	161.65	246.10	125.27	150.75	86.12	1190	10.78	470	14460.5685
14	449.85	172.93	254.55	134.91	161.19	89.46	1251	11.89	473	15277.5458
15	449.85	172.91	259.00	139.57	160.14	93.57	1263	12.05	490	15439.7262

16	448.38	172.02	254.77	136.31	160.34	90.01	1250	11.84	481	15263.9204
17	439.55	168.63	254.02	130.01	155.13	85.05	1221	11.38	480	14875.0470
18	436.47	162.99	252.10	133.59	153.38	74.47	1202	11.01	460	14620.0966
19	421.85	160.40	244.04	120.57	153.05	69.57	1159	10.47	484	14050.0492
20	416.04	139.50	240.19	109.82	135.22	60.62	1092	9.39	468	13172.3503
21	401.75	138.17	209.95	100.14	125.26	55.82	1023	8.09	427	12282.1841
22	392.32	129.99	209.89	91.46	117.84	50.14	984	7.64	440	11785.0055
23	390.92	126.68	208.93	92.28	114.09	50.42	975	7.45	398	11671.4532
24	388.65	126.77	207.82	78.71	115.41	50.05	960	7.41	330	11482.8012

Table 9 The optimal dispatches six unit system of HLIBCO

t/U	1	2	3	4	5	6	P_D	P_L	Iteration	Fuel cost
1	386.56	126.09	208.97	79.28	111.31	50.10	955	7.31	172	11419.7274
2	381.23	122.80	202.36	79.78	112.86	50.03	942	7.06	141	11256.8181
3	380.39	120.15	202.40	78.81	110.20	50.00	935	6.97	157	11169.4374
4	380.61	117.56	201.27	76.29	111.07	50.12	930	6.91	152	11107.3369
5	380.39	120.15	202.40	78.81	110.20	50.00	935	6.97	157	11169.4374
6	385.87	125.84	206.78	90.36	111.29	50.03	963	7.27	169	11520.0721
7	394.02	132.49	209.40	91.27	119.33	50.20	989	7.71	174	11848.2225
8	399.85	139.33	209.43	101.81	126.23	54.43	1023	8.08	178	12280.9808
9	417.67	160.49	241.25	109.88	139.46	67.15	1126	9.91	181	13615.8700
10	427.62	160.66	240.48	121.37	139.26	70.70	1150	10.10	175	13930.7601
11	436.56	162.66	246.65	127.22	153.75	85.13	1201	10.98	188	14606.7325
12	444.46	169.66	255.89	132.48	159.09	85.08	1235	11.65	183	15061.8516
13	434.59	162.33	248.06	128.28	152.87	74.73	1190	10.86	165	14460.0910
14	446.83	172.50	255.44	136.57	161.87	89.66	1251	11.88	135	15277.3400
15	449.70	173.98	258.36	140.20	163.43	89.43	1263	12.09	128	15439.5000
16	448.61	171.67	256.11	136.20	160.46	88.81	1250	11.86	148	15263.8340
17	439.94	166.41	252.39	131.41	156.98	85.23	1221	11.37	124	14873.9327
18	436.47	163.07	247.79	127.71	152.74	85.21	1202	10.99	176	14620.0496
19	427.74	160.68	241.00	121.64	150.23	68.09	1159	10.39	170	14049.3996
20	414.58	139.38	240.19	108.48	135.57	63.18	1092	9.37	176	13169.5644
21	399.85	139.33	209.43	101.81	126.23	54.43	1023	8.08	178	12280.9808
22	391.21	129.31	209.91	92.68	188.49	50.01	984	7.62	172	11784.8226
23	389.96	128.40	209.53	90.27	113.85	50.46	975	7.48	160	11671.1728
24	383.33	123.03	208.81	90.06	111.49	50.53	960	7.24	186	11482.5393

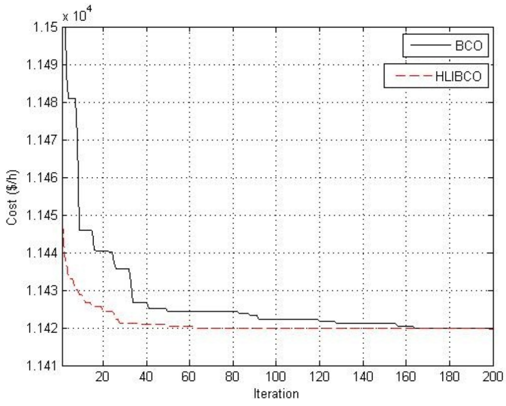

Fig. 4. Solution and convergence time of BCO and HLIBCO at load demand 955 MW

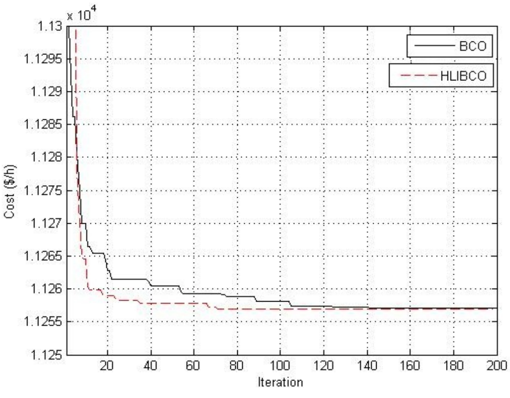

Fig. 5. Solution and convergence time of BCO and HLIBCO at load demand 942 MW

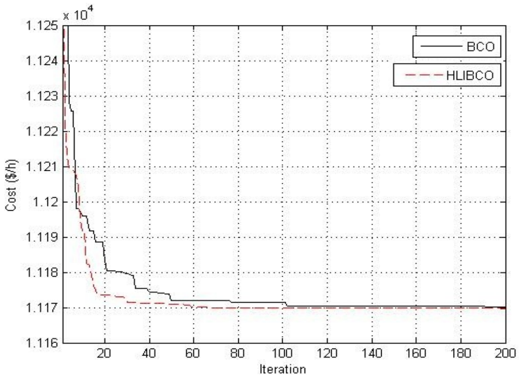

Fig. 6. Solution and convergence time of BCO and HLIBCO at load demand 935 MW

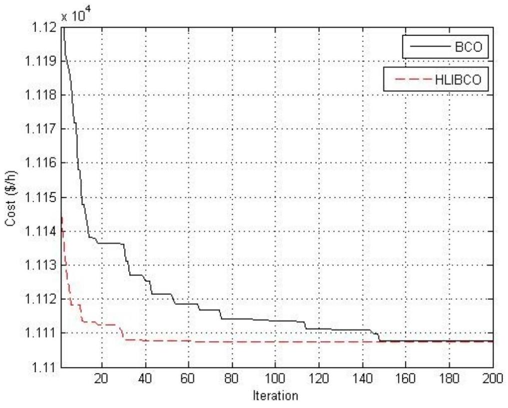

Fig. 7. Solution and convergence time of BCO and HLIBCO at load demand 935 MW

Table 10 Total cost comparison of case 2

Method	Total cost ($/day)	Power Loss (MW)
λ-Iteration [27]	313405.65	-
BM [27]	313405.40	-
SAMF [28]	313363.12	220.54
BCO	313388.52	222.54
HLIBCO	**313360.47**	**220.17**

Conclusion

This paper has indicates that a hybrid of the lambda iteration and bee colony optimization based techniques can be used to solve the economic dispatch problem within prohibited operating zones. This method provided fast and accurate results when compared with the conventional method. By using the HLIBCO method, execution time could also be reduced. In case studies, the proposed method produced better results in comparison with the 2PNN, PSO, HPSO, λ-iteration, BM, SAMF and BCO methods depending on the test conditions that were evaluated.

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