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Journal of American Science

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Multidisciplinary Academic Journal Publisher

Combined Heat and Power Economic Dispatch Using Artificial Bee Colony Algorithm

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Abstract: Combined heat and power economic dispatch is one of the key issues in power systems. Complexity of these issues increases when heat production units are added to it. Hence, in this paper a new method based on heuristic penalizing method and artificial bee colony algorithm for solving combined heat and power economic dispatch has been presented. Complexity and difficulty in solving simultaneous production of heat and electricity economic dispatch is related to the provisions of this problem is that this algorithm is easily able to satisfy these constraints. This optimization algorithm has a wide field of general search and this is effective in achieving optimized solutions by this algorithm. Application of artificial bee colony algorithm to solve the problem of combined heat and power economic dispatch has been tested in two samples and numerical results reveal the fact that this method has better and faster convergence in comparison to other existing methods to solve the problem.
[Mojtaba Hakimzadeh, Arsalan Najafi, Mahdi Hayatdavudi, Masoud Majd and Reza Sedaghati. **Combined Heat and Power Economic Dispatch Using Artificial Bee Colony Algorithm.** *J Am Sci* 2023;19(12):99-107]. ISSN 1545-1003 (print); ISSN 2375-7264 (online). http://www.jofamericanscience.org 05.doi:10.7537/marsjas191223.05.

Keywords: Artificial bee colony algorithm; Combined heat and power economic dispatch

1. Introduction

The issue of combined heat and power economic dispatch (CHPED) is of particular importance in power systems. This talk examines the heating units, power and cogeneration units that work simultaneously and its aim is finding optimal point for these units with considering all provisions and complications of the problem (Su et al., 2004).

So far, several analytical and developmental methods have been used in this field. Rooijers and Amerongen have proposed the two-layer strategy on CHPED in which the bottom layer solves the issue of economic dispatch for heat and power for given value of lambda, and updates the top layer of the lambda coefficients (Rooijers et al., 1994). This process continues until the amount of power and heat are met. Also, the branch and bound method is another way to solve this problem which has been proposed as a mathematic method (Makkonen et al., 2006; Rong et al., 2007). In addition to the mentioned mathematical methods several evolutionary optimization methods have been used in this area include: Harmony Search (HS) (Vasebi et al., 2007), Evolutionary Programming (EP) (Wong et al., 2002), Improved Ant Colony (ACO) (Song et al., 1999), Mesh Adaptive Direct Search Algorithm (MADS) and Economic Dispatch Harmony Search (EDHS) in the CHPED problem successfully have been implemented (Hosseini et al., 2011; Khorram et al., 2011). Self adaptive real coded genetic algorithm (SARGA) in (Subbaraj et al., 2009) has been proposed to solve this problem. This method of genetic algorithm uses tournament method for selection of solutions and for estimating some of their constraints use the penalty factors. Also, in (Song et al., 1998) a method based on genetic algorithm has been applied that uses the enhanced penalty coefficients. In (Dieu et al., 2009) the Augmented Lagrange Hopfield Network (ALHN) has been successful to solve the CHPED problem. In (Geem et al., in press) a new method has utilized in which the non-convex region is divided into two convex regions and then problem is solved.

In this paper a new method based on heuristic penalizing method and artificial bee colony algorithm has been used to solve CHPED. Simulations performed on two samples and the results were compared with existing methods. The results show the tangible superiority of the proposed method in achieving the optimum solution.

2. Problem Formulation

CHPED problem in fact is determining the heat and power production units in a manner that will minimize fuel costs while the demand for produced power and heat and a series of other provisions are satisfied. Output power of power-producing units and output heat of heat-producing units are characterized by their high and low limits. Also, for cogeneration units, as well as limitations is determined by the curve of Fig. 1 (ABCDEF) and indicates that the solutions are in a possible area that is within the curve. During the BC border curve the heat capacity increases while the power capacity is reduced and during the CD curve, the thermal capacity is reduced. Objective function and constraints of the CHPED problem are expressed as follows (Subbaraj et al., 2009):

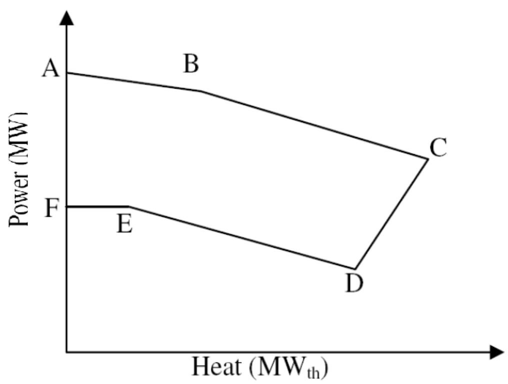

Fig. 1. A feasible operation region for the cogeneration units.

$$\min f_{\cos t} = \sum_{i=1}^{Np} C_i(P_i) + \sum_{j=1}^{Nc} C_j(P_j, H_j) + \sum_{k=1}^{Nh} C_k(H_k) \quad (1)$$

$$\sum_{i=1}^{Np} P_i + \sum_{j=1}^{Nc} P_j = P_d \quad (2)$$

$$\sum_{j=1}^{Nc} H_j + \sum_{k=1}^{Nh} H_k = H_d \quad (3)$$

$$P_i^{\min} \le P_i \le P_i^{\max} \qquad i = 1, \dots, N_p \quad (4)$$

$$P_j^{\min}(H_j) \le P_j \le P_j^{\max}(H_j) \qquad j = 1, \dots, N_c \quad (5)$$

$$H_j^{\min}(P_j) \le H_j \le H_j^{\max}(P_j) \qquad j = 1, \dots, N_c \quad (6)$$

$$H_k^{\min} \le H_k \le H_k^{\max} \qquad k = 1, \dots, N_h \quad (7)$$

With:

$$C_i(P_i) = a_i + b_i P_i + c_i P_i^2 \quad (8)$$

$$C_j(P_j, H_j) = a_j + b_j P_j + c_j P_j^2 + d_j H_j + e_j H_j^2 + f_j P_j H_j \quad (9)$$

$$C_k(H_k) = a_k + b_k H_k + c_k H_k^2 \quad (10)$$

In which:

$f_{\cos t}$ Total cost of fuel
C Production costs of the units
P Production power of heat-only units
T Produced thermal of heat-only units
O Production power of cogeneration units
H Produced heat of cogeneration units
H_d Heating demand of system
P_d Power demand of system
i Counting index of power-producing units
j Counting index of cogeneration units
k Counting index of heat-producing units
N_p Number of power-producing units
N_c Number of cogeneration units
N_k Number of heat-producing units.

$P_i^{\min}$ and $P_i^{\max}$ are power constraints and $H_i^{\min}$ and $H_i^{\max}$ are heat constraints. Also, b_i, a_i and c_i are fuel costs impact factors of the number i power-producing units, e_j, c_j, b_j, a_j and f_j are the factors of fuel costs of the cogeneration unit j and a_k, b_k and c_k are factors of fuel costs of heat generating units.

3. Optimization Based on Artificial Bee Colony Algorithm

3.1. Artificial bee colony algorithm

Artificial bee colony algorithm was introduced by Karaboga for the first time in 2005 (Sishaj et al., 2010). This algorithm has been obtained from simulating the behavior of bees in nature and is one of the optimization methods based on population. In this method bees' colony is divided in three groups of employed bees, supervisor and scout bees. Employed bees search the food sources randomly and share their findings. Here, the supervisor bees among the food sources according to their position and experience choose the appropriate food source while scout bees select food sources quite randomly regardless of experience. Every selected food source represents a possible solution in solving the problem. The amount of nectar available in the food source indicates fitness of the solution of the question. The number of employed bees is equal to supervisor bees and equal to the population of the problem. In this algorithm the initial population is randomly generated and in NS number in which NS indicates the number of food sources, and is equal to the number of employed bees. Each solution of $X_i = (x_{i1}, x_{i2}, ..., x_{in})$ is a vector of in dimensions. Then this population goes into the process of employed bees', supervisors' and scouts' search. In the ABC algorithm fitness function is defined as follows:

$$fit_i = \begin{cases} \frac{1}{1+f_i} & f \geq 0 \\ 1+|f_i| & f < 0 \end{cases} \qquad (11)$$

In which f_i is the value of objective function and fit_i is fitness of solution i after the generation of new solutions. Supervisor bees choose the food sources with p_i probability in which:

$$p_i = \frac{fit_i}{\sum_{j=1}^{NS} fit_j} \qquad (12)$$

New solutions are generated from previous solutions as following:

$$x_{ij}^{new} = x_{ij}^{old} + \lambda_{ij}(x_{ij}^{old} - x_{kj}^{old}) \quad \text{for } j = 1,2,...,n \qquad (13)$$

In the above equation k is a random number that is selected from the range $\{1,2,...,NS\}$. Also, λ_{ij} is a random number in range $[-1,1]$.

The new positions, after production and being fitted, are compared with the old positions and if they have a better quality (more nectar), they will be replaced. Also, if a position does not improve that source of food is declared abandoned and will be replaced by the scout bees according to the following introduced equation:

$$x_{ij}^{new} = l_j + rand(u_j - l_j) \qquad (14)$$

In which l_j and u_j are the high and low limit of variable x_{ij}, and $rand$ is random number between zero and one. After the new population was evaluated, the new population is selected among them. This applies as long as the number of iterations of the algorithm will finish (Karaboga et al., 2008).

3.2. Initializing population

In the proposed approach each bee is a possible solution of the problem and can be considered as a vector. In the CHPED problem, the determination of power and heat output of the generating units is the main object. Therefore, the position of bee f can be expressed as

$$X_f = [P_{f,1}, .., P_{f,Np}, P_{f,Np+1}, .., P_{f,Np+No}, H_{f,1}, .., H_{f,No}, H_{f,No+1}, .., H_{f,No+Nh}]$$

Initialization is randomly performed observing the equality and inequality constraints. First, one of the components l related to power output is selected randomly and takes a value in the related range of $[P_l^{min}, P_l^{max}]$ in a random fashion. Then, other components related to conventional power units and cogeneration units except one of them are randomly initialized in the range of $[P_l^{min}, P_d - \sum_{a=1}^{Ni} P_a]$, where Ni is the set of initialized units. Next, the final component value is equal to $(P_d - \sum_{a=1}^{Ni} P_a)$. If the solution does not satisfy feasible region of cogeneration units, it will be penalized that is described in the next section. Similarly, the components related to heat units are initialized.

3.3. Constraint handling and penalizing strategy

A. Inequality constraint

In the CHPED problem, power and heat output of units are inequality constraints, Esq (4,7). They are restricted by upper and lower bounds. When the solutions are initialized, their values are generated between their bounds. But they are violated after generating new solutions in local search. For satisfying inequality constraints, if production of the unit exceeds from upper bound, production will be set at upper bound and if production decreases from lower bound it will be set on lower bound.

B. Equality constraint

There are two quality constraints in CHPED problem. The load and heat demands satisfactions are the equality constraints Eqs (2,3). This process is done after satisfying inequality constraint. The initial population is generated so that the equality constraints are satisfied in it, but sum of the heat power and electrical power will be greater or lower than heat demand and power demand, respectively, in generating new populations. Therefore equality constraints may be violated and they must be repaired. In order to satisfy these constraints the surplus or shortage power from demands are divided among units. The procedure is conducted in respect to maximum and minimum capacities of the units; therefore inequality constraints will be not violated.

C. Feasible operation region of cogeneration units

Power and heat output of cogeneration units are mutually dependent. Therefore these constraints are introduced as feasible operation region constraints that they are very difficult to be met. In this paper a new penalizing method is proposed in which infeasible solutions are penalized in respect to their violations from feasible regions. In this method if the output of a cogeneration unit is outside the feasible region, a penalty factor depending on the minimum distance between the cogeneration unit output and feasible region border is employed. Fig. 2 shows the distance graphically. If $aH+bP+c=0$ is the equation of the nearest region border of the cogeneration unit (line AB in Fig.2), the minimum distance will be calculated using equation 15. Then a penalty factor is calculated using equation 16.

$$d=\frac{|aH_0+bP_0+c|}{\sqrt{a^2+b^2}} \qquad (15)$$

$$Penalty_i=pf\cdot\sum_{j=1}^{Nc}d_j \qquad (16)$$

where (H_0,P_0) is the output position of cogeneration unit, $Penalty_i$ is the penalty factor related to i^{th} solution and pf is a constant value. Therefore penalty amount depends on distance directly, and more distance will result in more penalties and vice versa. This process is done in both initializing and generating new solutions.

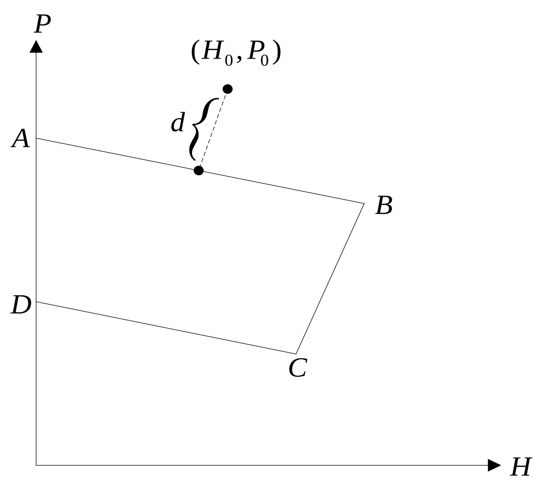

Fig. 2. The minimum distance between points outside of the feasible operation regions.

3.4. Matching the artificial bee colony algorithm and CHPED problem

CHPED problem has been solved using an optimization technique in which bees have information of power generating units. The optimization process for this problem is presented below:

Step 1: generating initial random population
Step 2: Satisfying constraints and penalizing infeasible solutions
Step 3: Evaluating solutions
Step 4: generating new solutions
Step 5: Satisfying constraints and penalizing infeasible solutions
Step 6: Evaluating and selecting the solutions
Step 7: If the convergence condition is met, quit, otherwise go to Step 4.
Also the flowchart in Fig. 3 graphically illustrates the above steps

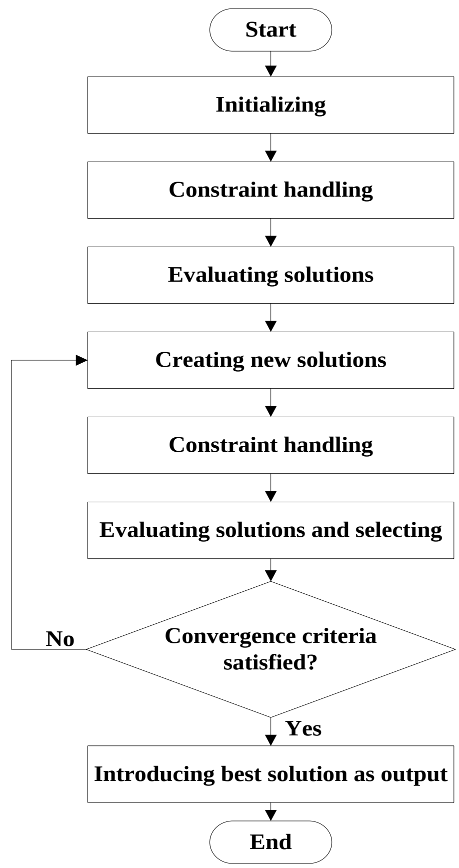

Fig. 3. Flowchart of the process of optimizing CHPED problem.

4. Simulation and Results of Numerical Studies

In this section, two cases have been considered to illustrate the performance of the proposed method. Case 1 is a typical system that all articles have conducted a simulation system on it. The second case also, is a system where fewer procedures are being implemented on it. Simulation of the proposed method has been done by using MATLAB software and a system with 1GigaBayte of RAM and a CPU 2180 dual core.

Case 1

This case includes a power generating unit, a heat generating unit, and two cogeneration units. The amount of power and thermal demand are 200 and 115 MW respectively. The possible performance region of cogeneration units are shown in Figures 4 and 5. Relations.... To ...... show cost function and constraints governing these cases.

$$\min f_{cost} = C_1(P_1) + \sum_{j=2,3} C_j(P_j, H_j) + C_4(H_4) \quad (17)$$

While:

$$C_1(P_1) = 50P_1 \quad (18)$$

$$C_2(P_2,H_2) = 2650 + 14.5P_2 + 0.0345P_2^2 + 4.2H_2 + 0.03H_2^2 + 0.031P_2H_2 \quad (19)$$

$$C_3(P_3,H_3) = 1250 + 36P_3 + 0.0435P_3^2 + 0.6H_3 + 0.027H_3^2 + 0.011P_3H_3 \quad (20)$$

$$C_4(H_4) = 23.4H_4 \quad (21)$$

With this constraint:

$$P_1 + P_2 + P_3 = P_d \quad (22)$$

$$H_2 + H_3 + H_4 = H_d \quad (23)$$

$$1.781914894H_2 - P_2 - 105.7446809 \le 0 \quad (24)$$

$$0.177777778H_2 + P_2 - 247.0 \le 0 \quad (25)$$

$$-0.169847328H_2 - P_2 + 98.8 \le 0 \quad (26)$$

$$1.158415842H_3 - P_3 - 46.88118818 \le 0 \quad (27)$$

$$0.151162791H_3 + P_3 - 130.6976744 \le 0 \quad (28)$$

$$-0.067681895H_3 - P_3 + 45.07614213 \le 0 \quad (29)$$

$$0 \le H_3 \le 32.4 \text{ if } P_3 = 125.8 \text{ and } 0 \le H_3 \le 15.9 \text{ if } P_3 = 44 \quad (30)$$

$$0.00 \le P_1 \le 150.00 \quad (31)$$

$$0.00 \le H_4 \le 2695.20 \quad (32)$$

Implementation result of ABC algorithm in this case with different number of populations and 100 time runs for each row have been showed in Table 1. This table shows that this algorithm has reached the optimum solution with all populations and increase in population has caused improvement in frequency of reaching optimal solution and therefore increase the running time of the program. It should be mentioned that the mentioned time is the one time run of the program. Fig. 6 also shows the convergence with mentioned population. The number of iterations in this case has been considered 1000. But for more clarity only 300 iterations are shown in Fig. 7. The figure also, shows the convergence of all the solutions and the best solution during running the program. Initially solutions are distributed in the search space, but they move to the optimum solution gradually that this important phenomenon is quite tangible in the figure. Power and heat output of cogeneration units are mutually dependent. The variations of cogeneration output in 300 iterations have been illustrated in Fig. 8 and 9. These figures verify the mutual dependency of cogeneration unit. Results of comparing the proposed method in this case with other cases have been listed in Table 2. which shows that it has reached optimum solution in less time than other methods.

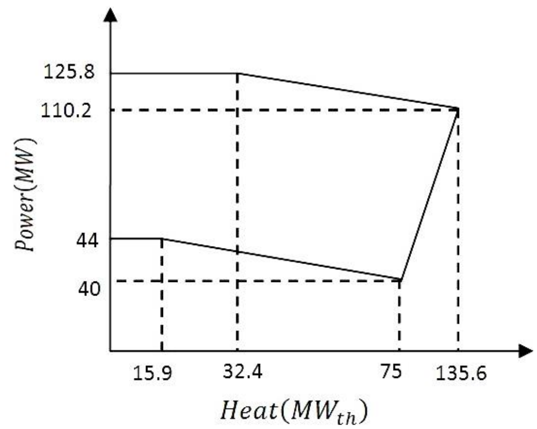

Fig. 4. Feasible region of unit 3 in case 1 and unit 2 in case 2.

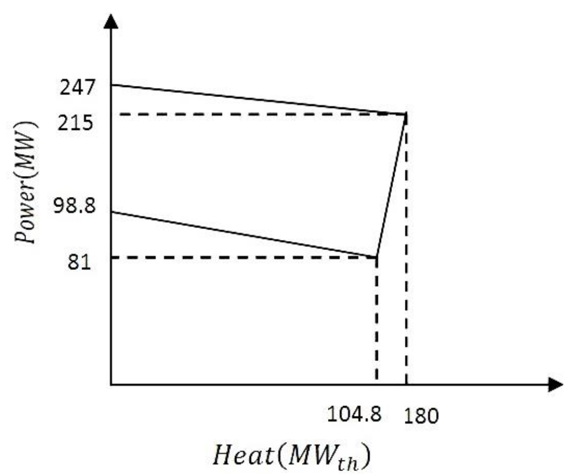

Fig. 5. Feasible region of unit 2 in case 1.

Table 1. Results of proposed method with different populations in case 1

No. population	Best solution	Mean solution	Worst solution	Standard deviation	CPU time(s)
25	9257.07	9259.51	9267.35	2.63	1.76
50	9257.07	9257.91	9260.13	0.79	2.06
75	9257.07	9257.82	9262.08	1.02	2.44
100	9257.07	9257.26	9257.67	0.15	2.75

Table 2. Comparison of the results of the proposed method with other methods in case 1

Method	P1	P2	P3	H2	H3	H4	Pd	Hd	Cost($)	Time(s)
Lagrangian Relaxation	0.00	160.00	40.00	40.00	75.00	0.00	200.00	115.00	9257.07	3.98
B & B	0.00	160.00	40.00	40.00	75.00	0.00	200.00	115.00	9257.07	4.27
ACSA	0.08	150.93	49.00	48.84	65.79	0.37	200.01	115.00	9452.2	5.26
GA_PF	0.00	159.23	40.77	39.94	75.06	0.00	200.00	115.00	9267.28	4.32
PSO	0.05	159.43	40.57	39.97	75.03	0.00	200.00	115.00	9365.1	3.09
EP	0.00	160.00	40.00	39.99	75.00	0.00	200.00	115.00	9257.1	7.96
IGAMU	0.00	160.00	40.00	39.99	75.00	0.00	200.00	114.99	9257.09	5.53
HS	0.00	160.00	40.00	40.00	75.00	0.00	200.00	115.00	9257.07	4.21
SARGA	0.00	160.00	40.00	40.00	75.00	0.00	200.00	115.00	9257.07	3.76
ALHN	0.00	159.99	40.00	39.99	75.00	0.00	199.99	114.99	9257.05	---------
Proposed method	**0.00**	**160.00**	**40.00**	**40.00**	**75.00**	**0.00**	**200.00**	**115.00**	**9257.07**	**2.75**

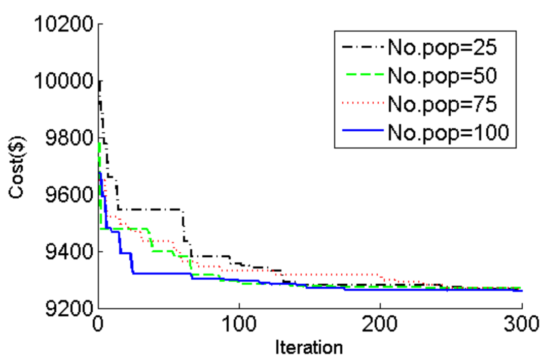

Fig. 6. Graph of convergence with different populations in Case 1

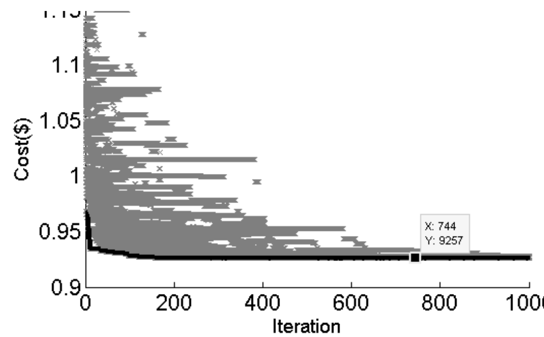

Fig. 7. Graph of convergence of the best solution and all solutions in Case 1

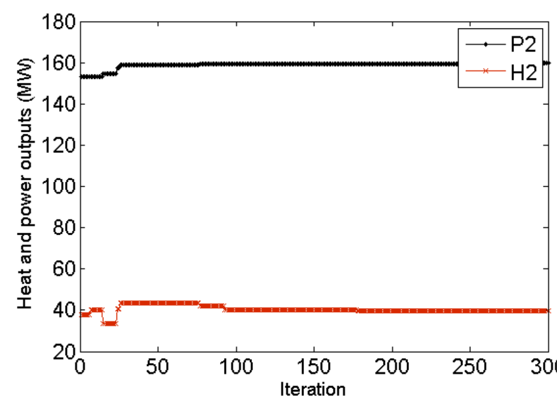

Fig. 8. Variations of cogeneration units output in all iterations for unit 2 in case 1

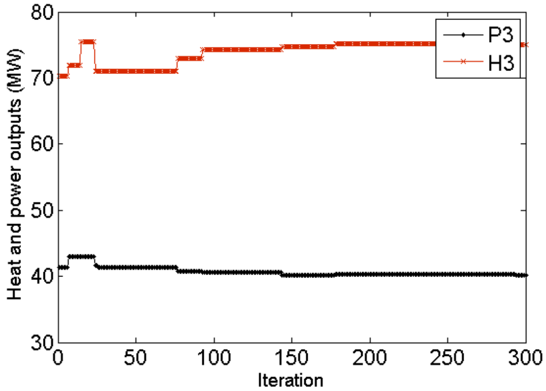

Fig. 9. Variations of cogeneration units output in all iterations for unit 3 in case 1

Case 2

In order to display the efficiency of proposed method in solving more complex problems, a case with more units and more complex performance area has been considered. This case has a power generating unit, a heat generating unit and three cogeneration units. Possible performance areas are shown in Figures 8 and 9. Cost function and constraints governing this

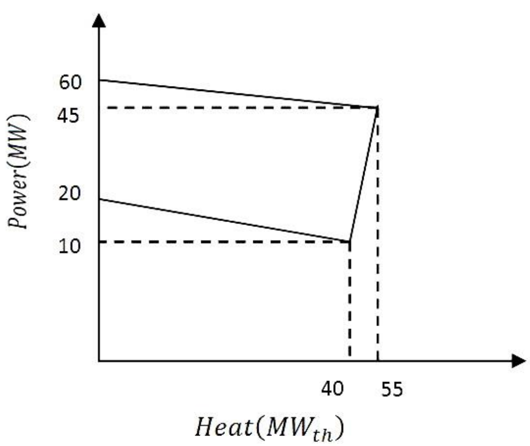

Fig. 8. Feasible region of unit 3 in case 2

With this constraint:

$$P_1+P_2+P_3+P_4=P_d \quad (39)$$

$$H_2+H_3+H_4+H_5=H_d \quad (40)$$

$$-0.25H_3-P_3+20\leq 0 \quad (41)$$

$$2.33333333H_3-P_3-83.3333333333\leq 0 \quad (42)$$

$$0.272727272727H_3+P_3-60\leq 0 \quad (43)$$

$$2.2H_4-P_4-8.99999999\leq 0 \quad (44)$$

$$0.6H_4+P_4-105\leq 0 \quad (45)$$

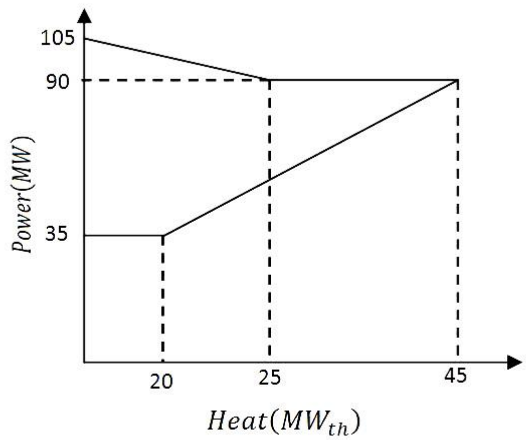

Fig. 9. Feasible region of unit 4 in case 2.

$$\min f_{cost}=C_1(P_1)+\sum_{j=2,3,4}C_j(P_j,H_j)+C_5(H_5) \quad (33)$$

$$C_1(P_1)=2548.863+7.6997P_1+0.00172P_1^2+0.000115P_1^3 \quad (34)$$

$$C_2(P_2,H_2)=1250+36P_2+0.0435P_2^2+0.6H_2+0.027H_2^2+0.011P_2H_2 \quad (35)$$

$$C_3(P_3,H_3)=2650+34.5P_3+0.1035P_3^2+2.2203H_3+0.025H_3^2+0.051P_3H_3 \quad (36)$$

$$C_4(P_4,H_4)=1565+20P_4+0.072P_4^2+2.3H_4+0.02H_4^2+0.04P_4H_4 \quad (37)$$

$$C_5(H_5)=950+2.0109H_5+0.038H_5^2 \quad (38)$$

Table 3. Comparison of the results of the proposed method with other methods in case 1

Method	Demand		Unit1	Unit2		Unit3		Unit4		Unit5	Total cost
	P_D	H_D	P_1 (MW)	P_2 (MW)	H_2 (MW)	P_3 (MW)	H_3 (MW)	P_4 (MW)	H_4 (MW)	H_5 (MW)	
GA	300	150	135.00	70.81	80.54	10.84	39.81	83.28	0.00	29.64	13779.50
HS			134.74	48.20	81.09	16.23	23.92	100.85	6.29	38.70	13723.20
EDHS*			135.00	18.16	84.06	13.07	37.76	133.76	0	28.11	13613
Proposed method			**134.976**	**42.431**	**74.287**	**17.785**	**34.162**	**104.808**	**0.049**	**41.501**	**13675.41**
GA	250	175	119.22	45.12	78.94	15.82	22.63	69.89	18.40	54.99	12327.37
HS			134.67	52.99	85.69	10.11	39.73	52.23	4.18	45.40	12284.45
EDHS*			135.00	0.11	85.82	0	56.32	114.89	0	32.81	11836
Proposed method			**134.998**	**40.031**	**74.742**	**10.036**	**40.008**	**64.934**	**14.49**	**45.631**	**12117.36**
GA	160	220	37.98	76.39	106.00	10.41	38.37	35.03	15.84	59.97	11837.40
HS			41.41	66.61	97.73	10.59	40.23	41.39	22.83	59.21	11810.88
EDHS*			135	0	87.256	0	58.1586	25	40.1823	34.37	9318.1
Proposed method			**42.589**	**65.488**	**96.978**	**10.538**	**40.230**	**41.385**	**22.902**	**59.870**	**11770.51**

* Proposed solutions by this method are out of the feasible operation regions.

$$0 \le H_4 \le 20 \quad \text{if} \quad P_4 = 35 \tag{46}$$

$$35 \le P_1 \le 135 \tag{47}$$

$$0.00 \le H_5 \le 60 \tag{48}$$

This case has been solved with different demands and the results have been compared to other methods listed in Table 2. The results indicate the ability of the proposed method compared with other methods. Since the proposed method has reached more optimal solution than others. In this table also, the EDHS shows less value for the cost, while the solutions provided by this method is out of the feasible operation regions.

5. Conclusion

In this paper a new method has been presented to solve CHPED problem based on artificial bee colony algorithm. Also, an innovative approach has been introduced to satisfy the constraints based on penalty factors. The proposed method has very well met all constraints with the least cost. To display the efficiency of proposed method, artificial bee colony algorithm implemented in two standard systems and the results have been compared with other methods. Comparing the results show a clear superiority of the proposed method in comparison with other methods.

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References

[1] C.T. Su, C.L. Chiang, An incorporated algorithm for combined heat and power economic dispatch, *Electric Power Systems Research, vol. 69, n. 2-3,* 2004, pp. 187–195.

[2] F.J. Rooijers, V. Amerongen RAM, Static economic dispatch for co-generation systems, *IEEE Transactions on Power Systems*, *vol. 9, n. 3,* 1994, pp. 1392–1398.

[3] S. Makkonen, R. Lahdelma, Non-convex power plant modeling in energy optimization. *European* Journal *of Operational Research, vol. 171, n.3*, 2006, pp. 1113–1126.

[4] A. Rong, R. Lahdelma, An efficient envelope-based branch-and-bound algorithm for non-convex combined heat and power production planning, *European Journal* of *Operational Research*, *vol. 183, n. 1*, 2007, pp. 412–431.

[5] A. Vasebi, M. Fesanghary,S.M.T. Bathaee, Combined heat and power economic dispatch by harmony search algorithm, *International Journal of Electrical Power and Energy Systems*, *vol. 29, n. 10,* 2007, pp. 713–719.

[6] K.P.Wong, C. Algie, Evolutionary programming approach for combined heat and power dispatch, *Electric Power Systems Research*, *vol. 61, n. 3, 2002,* pp. 227–232.

[7] Y.H. Song, C.S. Chou, T.J. Stonham, Combined heat and power dispatch by improved ant colony search algorithm, *Electric Power Systems Research*, *vol. 52, n. 2, 1999,* pp. 115–121.

[8] S.S. Hosseini, A. Jafarnejad, A.H. Behrooz, A.H. Gandomi, Combined heat and power economic dispatch by mesh adaptive direct search algorithm, *Expert Systems application*, *vol. 38, n. 6*, 2011, pp. 6556-6564.

[9] E.Khorram, M.Jaberipour, Harmony search algorithm for solving combined heat and power economic dispatch problems, *Energy Conversion and Management*, *vol. 52,n. 2*, 2011, pp. 1550–1554.

[10] P. Subbaraj, R. Rengaraj, S. Salivahanan, Enhancement of combined heat and power economic dispatch using self adaptive real-coded genetic algorithm, *Applied Energy*., *vol. 86, n. 6,* 2009, pp. 915–921.

[11] Y.H. Song, Q.Y. Xuan, Combined heat and power economic dispatch using genetic algorithm based penalty function method, *Electric Power Components and System*s, *vol. 26, n. 4*, 1998, pp. 363–372.

[12] V.N. Dieu, W. Ongsakul, Augmented Lagrange Hopfield network for economic load dispatch with combined heat and power, *Electric Power Components and System*s, *vol. 37, n. 12,* 2009, pp. 1289–1304.

[13] Z.W. Geem, Y.H. Cho, Handling non-convex heat-power feasible region in combined heat and power economic dispatch, *Electric Power and Energy Systems, in press*.

[14] S.H. Sishaj, P. Simon, Artificial bee colony algorithm for economic load dispatch problem with non-smooth cost functions, *Electric Power Components and System*s, *vol. 38, n. 7,* pp. 786-803, 2010.

[15] D. Karaboga, B. Basturk, On the performance of artificial bee colony (ABC) algorithm, *Applied Soft Computing, vol. 8, n. 1,* pp. 687–697, 2008.

12/2/2023