Combined Heat and Power System Operation Cost Minimization using Frog Leaping Based Intelligent Search Algorithm

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Combined heat and power (CHP) systems have been utilized more and more in power systems, recently. With the increasing penetration of CHP-based co-generation of electricity and heat, determination of economic dispatch of power and heat becomes a more complex and challenging task. In this paper, the optimal operation of CHP-based system is studied and an algorithm is proposed for solution of it. The optimal operation of CHP-based systems or CHP economic dispatch is inherently a nonlinear and non-convex optimization problem with a lot of local optimal solutions. In this paper, frog leaping algorithm is used for solution of the problem. This heuristic algorithm is well capable to attain the optimal solutions even in the case of non-convex optimization problems. The proposed method is implemented on several standard test systems. The obtained results have been compared with other intelligent search algorithms. The numerical simulations verify that optimal operation of CHP systems can result in a large economic annual saving. © 2018 Journal of Energy Management and Technology

keywords: *Combined Heat and Power System; non-convex optimization; intelligent search algorithm*

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1. INTRODUCTION

A. Motivation and problem statement

A simple combined heat is known as one of the most practical opinions for decreasing the environmental pollutions as well as increasing the overall efficiency of thermal power plants. In addition, power generation which is known as combined heat and power (CHP) or cogeneration traps heat from a power plant and sends it around to interested consumers. Hence, the reference [1] shows that cogenerating plants have the ability of generating both heat and electrical power with better energy efficiency and fuel utilization. In order to attain CHP systems higher efficiency, it grabbed more attention in recent years. In [2,3] the network loss reduction and rabid return of investment are compared to conventional systems. In cogeneration, the internal combustion engines or micro turbines are used which produce electricity and useful heat, simultaneously. Due to the costs of insulation heat pipes, it is better the generated heat by the cogeneration units to be consumed locally while the generated electricity can be consumed locally or delivered to the transmission network. The fuel of combined heat and power (CHP) units are usually fossil fuels and mainly natural gas [4,5]. One of the main problems in the operation of multi-unit production systems are to determine the amount of optimal production of each unit. In CHP units, economic dispatch problem is defined as determination of the power and heat production of each unit in order to meet the needed electricity and heat with the lowest cost, and considers all limitations. One of the significant constraints which has complicated the solution of economic dispatch problem of CHP units is the interdependence of electricity and heat of a CHP units to each other. In fact, it can't be dependently determined the amount of electricity and heat which is produced by each unit. This interdependence is defined as an area which is non-convex for some of CHP units. The other factor of complexity of this issue is the non-linear, non- convex and non-differentiable function relationship between cost and power production which causes the problem to have several local optimum solutions, and the use of mathematical methods for solving this problem is limited.

B. Review of related works and contribution

According to the non-convex optimization problem, none of the mathematical methods (mainly based on gradient act) are not able to find the optimum point and ensure its optimality. Therefore, many efforts are done in order to improve the solutions by using intelligent optimization methods in recent years. In [6], a method based on ant colony algorithm is presented for solving the CHP economic dispatch problem. The improved version of genetic algorithm is given in reference [7] have been proposed in order to solve this problem. In [4, 8], the harmony search algorithm is used for the solution. In these references, the cost function is approximated by using third-degree polynomial and the effects of steam valves, which cause the non-convexity of cost function are not considered. In order to minimize the operation cost of combined heat and power system, the particle swarm optimization (PSO) has been proposed in [9]. In these papers, three types of production systems, including CHP systems, justly electricity production systems and heat production systems (boilers) are intended. In order to solve the CHPED, other evolutionary methods are implemented such as improved ant colony search algorithm [10], enhanced firefly algorithm [11], direct search method [12], artificial immune system [13], bee colony optimization [14], differential evolution [15], hybrid time varying acceleration coefficients-gravitational search algorithm-particle swarm optimization (hybrid TVAC-GSA-PSO) [16], time varying acceleration coefficients particle swarm optimization (TVAC-PSO) [17], improved group search optimization (IGSO) [18], whale optimization algorithm (WOA) [19], invasive weed optimization [20] , and augmented Lagrange combined with Hopfield neural network [21].

This paper presents implementation of frog leaping algorithm as a new and efficient meta-heuristic optimization method for solving economic dispatch of the combined heat and power systems. Valve point effect and CHP feasible operation regions as two influential features of the CHP systems are taken into account in the presented formulation which make the problem non-convex and hard to solve. The proposed method are implemented on two test systems which the results demonstrate the superiority of the proposed method over other meta-heuristic methods.

C. Paper organization

The rest of this article has been classified as follows: In the second section the formulation of the problem is discussed. The third section of the article is dedicated to introduce the utilized optimization algorithm. The result of simulation and its comparison with other methods have been performed in section 4. Section 5 includes the conclusion of the article.

2. PROBLEM FORMULATION

A. CHP economic dispatch problem model

The objective function of the problem is to minimize the overall cost of serving required electricity and heat demands. The costs of the units are commonly stated as quadratic nonlinear functions of produced electricity and heat. In addition to the complexity due to the nonlinearity of the objective function, the problem consists of remarkable equality and inequality constraints. The equality constraints imply that the produced electricity and heat should be equal to the electricity and heat demands across the network. The inequality constraints model the feasible operation boundaries of the devices. These constraints for power- and heat-only units are relatively simple, i.e. restricting energy output of these units to their minimum and maximum levels. However, for CHP units, these constraints are slightly more complicated. Since the produced electricity and heat of CHP units depend on each other, a feasible operation region is defined for each CHP unit. The produced electricity and heat of each CHP should be within this region. The objective function of the problem is presented in Eq. (1).

$$\min \sum_{i=1}^{N_p} C_i(P_i^p) + \sum_{j=1}^{N_c} C_j(P_j^c, H_j^c) + \sum_{k=1}^{N_h} C_k(H_k^h) \qquad (\$/h) \tag{1}$$

where $C_i(P_i^p)$, $C_j(P_j^c, H_j^c)$ and $C_k(H_k^h)$ denote to fuel costs of power-only, CHP and heat-only units, respectively. The indices of power-only, CHP and heat-only units are denoted as i, j and k, respectively, and N_p, N_c and N_h are the number of power-only, CHP and heat-only units, respectively.

The fuel cost of the power-only units is generally approximated by quadratic function as stated in Eq. (2).

$$C_i(P_i^p) = \alpha_i (P_i^p)^2 + \beta_i P_i^p + \gamma_i \qquad (\$/h) \tag{2}$$

where α_i, β_i and γ_i are coefficients of fuel cost functions of the power-only units.

The effect of steam valves on the cost of the power-only units is not negligible. The objective function should be modified as follows to incorporate the steam valve effect [22].

$$C_i(P_i^p) = \alpha_i (P_i^p)^2 + \beta_i P_i^p + \gamma_i + \left| \lambda_i \, sin(\rho_i (P_i^{p_{\min}} - P_i^p)) \right| \qquad (\$/h) \tag{3}$$

where λ_i and ρ_i are the corresponding valve effect modeling coefficients.

The cost function of the CHP units can be stated as Eq. (4).

$$C_j(P_j^c, H_j^c) = a_j (P_j^c)^2 + b_j P_j^c + c_j + d_j (H_j^c)^2 + e_j H_j^c + f_j H_j^c P_j^c \qquad (\$/\text{h}) \tag{4}$$

where a_j, b_j, c_j, d_j, e_j are the cost coefficients of the jth CHP unit. P_j^c and H_j^c are produced electricity and heat of the jth CHP unit, respectively.

The cost function of the boilers as heat-only units is presented in Eq. (5).

$$C_k(H_k^h) = a_k (H_k^h)^2 + b_k H_k^h + c_k \qquad (\$/h) \tag{5}$$

where a_k, b_k and c_k are the cost coefficients of the k-th boiler.

The problem's equality constraints are corresponding to satisfaction of electricity Eq. (6) and heat Eq. (7) demands.

$$\sum_{i=1}^{N_p} P_i^p + \sum_{j=1}^{N_c} P_j^c = P_D \tag{6}$$

$$\sum_{j=1}^{N_c} H_j^c + \sum_{k=1}^{N_h} H_k^h = H_D \tag{7}$$

where P_D and H_D are system electricity and heat demands.

The inequality constraints represent the allowable operation regions of the units. The electricity generation of power-only units are restricted to the allowed minimum $P_i^{p_{\min}}$ and maximum $P_i^{p_{\max}}$ generation in Eq. (8).

$$P_i^{p_{\min}} \le P_i^p \le P_i^{p_{\max}} \quad i = 1, \cdots, N_p \tag{8}$$

The inequality constraints for the CHP units are as follows:

$$P_j^{c_{\min}}(H_j^c) \le P_j^c \le P_j^{c_{\max}}(H_j^c) \qquad j = 1, \cdots, N_c \tag{9}$$

$$H_j^{c_{\min}}(P_j^c) \le H_j^c \le H_j^{c_{\max}}(P_j^c) \qquad j = 1, \cdots, N_c \tag{10}$$

Note that in spite of the power-only units, the electricity and heat production boundaries depend on each other as mentioned earlier. Therefore, the minimum and maximum heat and electricity production depends on the other one. For example, the minimum power output $P_j^{c\min}(H_j^c)$ is a function of the heat production. Two types of the heat and power feasible operation regions are shown in Figure 1 and Figure 2.

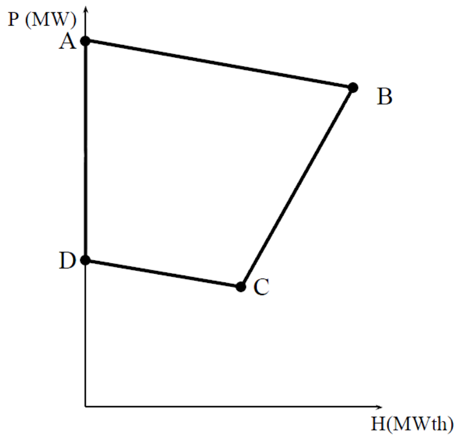

Fig. 1. A Typical heat-power feasible regions for a CHP unit type I.

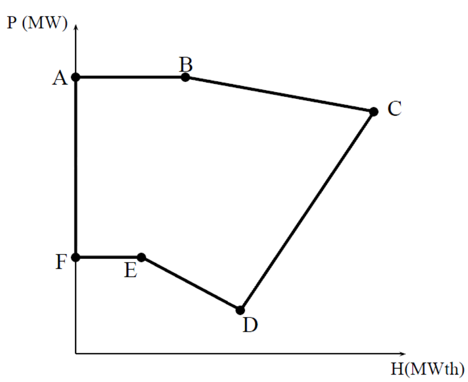

Fig. 2. A Typical heat-power feasible regions for a CHP unit type II.

The heat production limits for the boilers are as follows:

$$H_k^{h\min} \leq H_k^h \leq H_k^{h\max} \qquad k = 1, \cdots, N_h \tag{11}$$

where, $H_k^{h\min}$ and $H_k^{h\max}$ denote to minimum and maximum heat production of boiler , respectively.

B. Shuffled frog-leaping algorithm

Shuffled frog-leaping algorithm is a meta-heuristic optimization method devised to solve combinatorial optimization problems. The core of this algorithm is meme, i.e. information which can be exchanged by social interaction. The SFLA is a population-based approach similar to the other meta-heuristic optimization methods. The population is comprised of individuals as hosts of the memes in SLFA. The search is started by random population which reflect swap. The swamp is divided into communities called memeplexes. The frogs which belong to a memeplex affect on the other members. In each community (memeplex), frogs with better memes (information) contribute more in society development. In addition, the communities exchange their information to reach better results. The SLFA method is presented in Figure 3 and Figure 4.

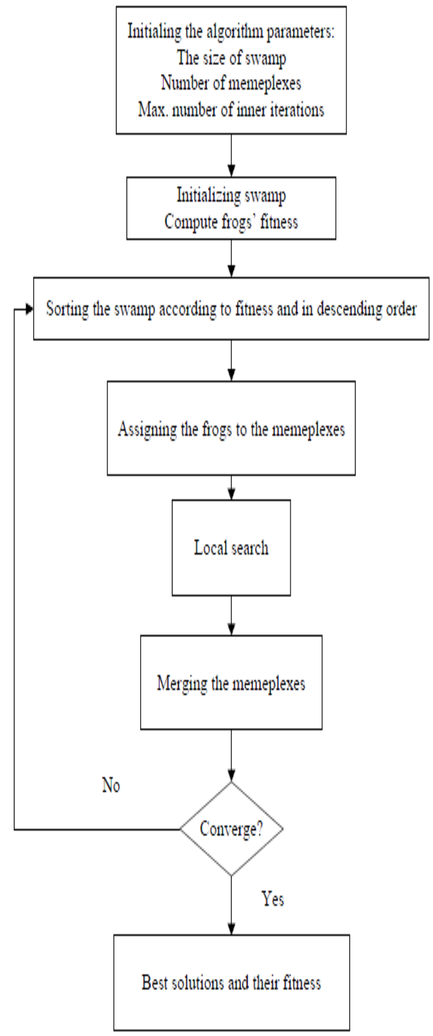

Fig. 3. The frog algorithm.

The population, i.e. swamp, consists of P frogs, where each frog is a solution for the problem. For an optimization problem with S decision variables, the i-th frog is as follows:

$$X_i = (x_{i1}, x_{i2}, ..., x_{iS}) \tag{12}$$

The swamp is divided into m memeplexes, where each memeplex has n frogs. In eacj memeplex, the best and the worst frogs are denoted as X_b and X_w, respectively. Moreover, the best frog across the population is denoted as X_g. The position of the worst frog in each memeplex is updated by employing the position of the best memeplex's frog.

$$X_n = X_w + rand().(X_b - X_w) \tag{13}$$

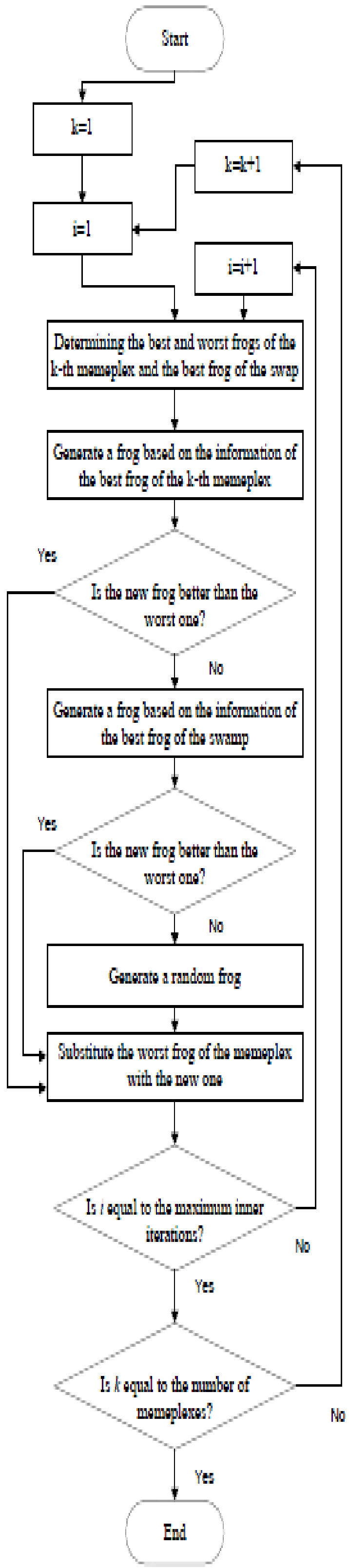

Fig. 4. Local search of the frog leaping algorithm.

where function $rand(.)$ generate uniformly distributed random values between 0 and 1. In a similar fashion, the position of the memeplex's worst frog may be updated by using the position of the best frog of the swamp as follows:

$$X_n = X_w + rand().(X_g - X_w) \quad \textbf{(14)}$$

The sequence and the algorithm of searching and updating within each memeplex are shown in Figure 4.

3. NUMERICAL STUDIES

In this section, the results of the simulations on two test systems are presented to evaluate the effectiveness of the proposed method. The data of the test systems, the simulations' results and eventually the comparison of the results of the proposed method with the other methods in the literature will be provided.

A. Test system I

The test system I includes a power-only unit, two CHP units and a boiler. The cost function of the power-only and boiler are as follows:

$$C_1(P_1) = 50 \times P_1, 0 \leq P_1 \leq 150MW \quad \textbf{(15)}$$

$$C_4(H_4) = 23.4 \times H_4, 0 \leq P_1 \leq 2695.2MWth \quad \textbf{(16)}$$

Moreover, the cost function coefficients of the CHP units are provided in the Table 1. In Table 2, the feasible operation regions of the CHP units of the test system I are provided.

Table 1. Cost function coefficients of the CHP units of test system I.

Unit	a	b	c	d	e	f
2	0.0345	14.5	2650	0.03	4.2	0.031
3	0.0435	36	1250	0.027	0.6	0.011

Table 2. Vertices of the feasible operation regions of the CHP units of test system I.

Unit 2	[98.8,0], [81,104.8], [215,180], [247,0],
Unit 3	[44,0],[44,15.9],[40,75],[110.2,135.6],[125.8,32.4],[125.8,0]

These feasible operation regions are depicted in Figure 5 and Figure 6, for first and second CHP units of the test system I, respectively.

The electricity and heat demands of the test system I are 200 MWh and 150 MWh-th, respectively.

The convergence curve of the proposed method for the test system I is depicted in Figure 7. As can be seen in this figure, the optimization algorithm converges in very low iterations.

The results of the proposed method and its comparison with the methods IACS, PSO, IGA, SARGA, HS, EDHS, GA-PF, SPSO and CPSO are provided in Table 3. According to the results, the proposed method attains the optimum solution for the problem compared with the other methods in a very low iterations.

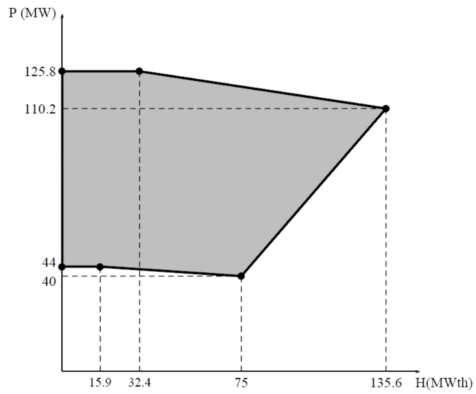

Fig. 5. Feasible operation region of the first CHP unit of the test system I.

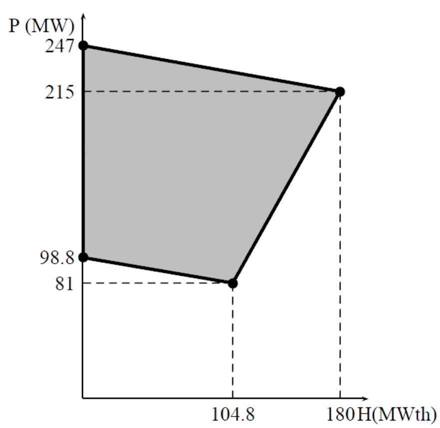

Fig. 6. Feasible operation region of the second CHP unit of the test system I.

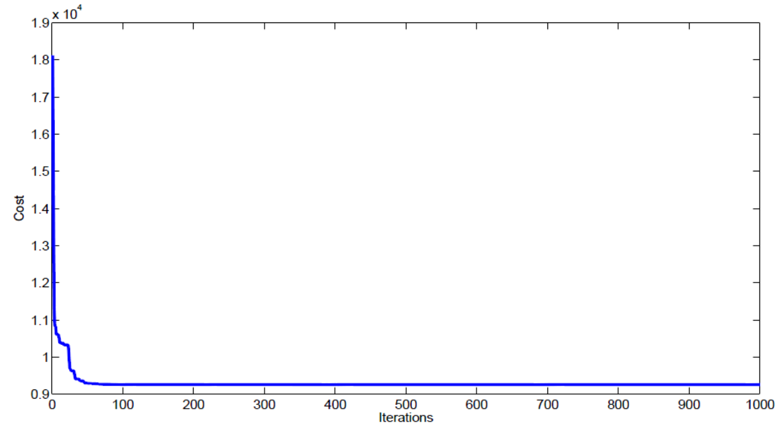

Fig. 7. The cost convergence curve of the proposed algorithm for test system II for load profile 1.

Table 3. Comparison of simulation results for Case I.

Output	IACS [4]	PSO [8]	IGA [5]	SARGA [21]	HS [6]	EDHS* [7]	GA_PF [22]	SPSO* [23]	**Proposed**
P_1	0.08	0.05	0	0	0	0	0	0	0
P_2	150.93	159.43	160	159.99	160	200	159.23	159.7065	160
P_3	49	40.57	40	40.01	40	0	40.77	39.9097	40
H_2	48.84	39.97	39.99	39.99	40	0	39.94	40	40
H_3	65.79	75.03	75	75	75	115	75.06	75	75
H_4	0.37	0	0	0	0	0	0	0	0
TP[a]	200.01	200.05	200	200	200	200	200	199.6162	200
TH[b]	115	115	114.99	114.99	115	115	115	115	115
TC[c]	9452.2	9265.1	9257.09	9257.07	9257.07	8606.07	9267.28	9248.17	**9257.07**

[a]Total Power (MW) [b]Total Heat (MWth) [c]Total Cost ($) * Not feasible

B. Test system II

This test system comprises a power-only unit, three CHP units and a boiler. The cost functions of the power-only unit and boiler are presented in Eq. (17) and Eq. (18), respectively.

$$C_1(P_1) = 0.000115 \times P_1^3 + 0.00172 \times P_1^2 + 7.6997 \times P_1 + 254.8863 \qquad 35 \leq P1 \leq 135MW \tag{17}$$

$$C_5(H_5) = 0.038 \times H_5^2 + 2.0109 \times H_5 + 950, \qquad 0 \leq H_5 \leq 60MWth \tag{18}$$

The coefficients of the cost functions of the CHP units as well as the vertices of the feasible operation regions of which are provided in Table 4 and Table 5, respectively. Three different load levels exist which presented in Table 6. Therefore the optimization problem should be solved three times for each of these load levels. These load levels comprise different load states. For example, the heat demand is more than the electricity demand in the first load level whereas the electricity demand is higher than the heat demand in the second one. The convergence curve of the proposed method for three different load levels are shown in Figure 8. As seen in this figure, the proposed method converges for all load levels. For all load levels of the test system II, convergence takes place in lower than 800 iterations. In order to evaluate the effectiveness of the proposed method, the results of the method are compared with the results of the harmony search (HS), genetic algorithm (GA) and economic dispatch harmony search (EDHS) methods. These comparisons are presented in Table 7, Table 8 and Table 9 for the first, second and third load levels, respectively.

Table 4. Cost function coefficients of the CHP units of test system II.

Unit	a	b	c	d	e	f
2	0.0435	36	1250	0.027	0.6	0.011
3	0.1035	34.5	2650	0.025	2.203	0.051
4	0.072	20	1565	0.02	2.34	0.04

Table 5. Vertices of the feasible operation regions of the CHP units of test system II.

Unit 2	[44,0], [44,15.9],[40,75],[110.2,135.6], [125.8,32.4],[125.8,0]
Unit 3	[20,0],[10,40], [45,55],[60,0]
Unit 4	[35,0],[35,20],[90,45],[90,25], [105,0]

Table 6. Electricity and heat demands of test system II.

	Electricity demand (Mwh)	Heat demand (Mwh-th)
Load level 1	150	300
Load level 2	250	175
Load level 3	160	220

According to the results, the proposed method obtains better solutions for all three load levels compared with the HS, GA and EDHS methods. Note that, the solutions of the proposed method are in the feasible operation regions of the CHP units and supply both electricity and heat demands in all three load levels as well. However, the solutions of the EDHS method do not supply demands and thus the costs of them are lower. It is worthy to mention that the reported results of the EDHS method are not even solutions for the problem since they are violate constraints of the optimization problem. Therefore, the lower cost of the EDHS method is not valid.

4. CONCLUSION

In this paper, a meta-heuristic optimization method is proposed to minimize the operation cost of the heat and power systems or the economic dispatch problem. Various specifications of the devices such as valve point effect, feasible operation region and the

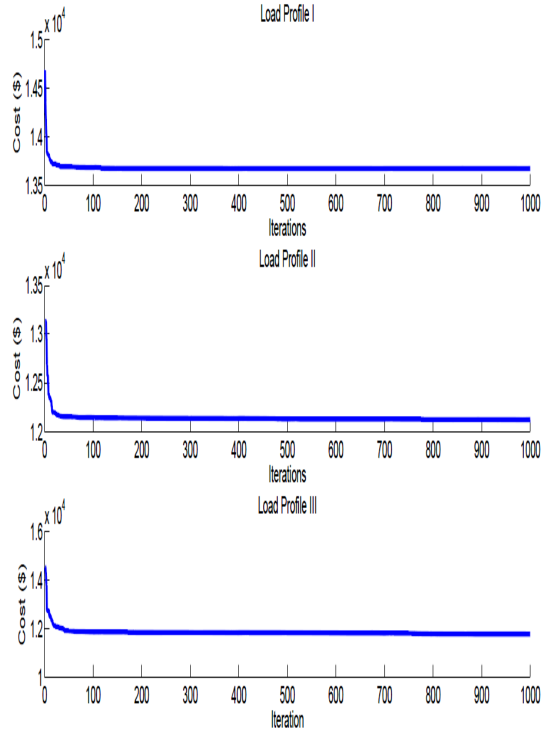

Fig. 8. The cost convergence curve of the proposed algorithm for test system II.

Table 7. Comparison of optimal results for the first load level of test system II.

Method	P_1	P_2	P_3	P_4	H_2	H_3	H_4	H_5	$\sum P$	$\sum H$	Total Cost
HS [6]	134.74	48.20	16.23	100.85	81.09	23.92	6.29	38.70	300.02	150.00	13723.20
GA [6]	135.00	70.81	10.84	83.28	80.54	39.81	0.00	29.64	299.93	149.99	13779.50
EDHS* [7]	135.00	18.1563	13.0749	133.7688	84.0626	37.7657	0.00	28.1118	300.00	149.9401	13613.00
TVAC-PSO [15]	135.000	41.402	18.598	105.000	73.356	37.429	0.000	39.214	300.00	150.000	13672.889
Proposed	134.88	42	18.12	105	74.87	36.59	0	38.54	300.00	150.00	**13676.3324**

*Not feasible

Table 8. Comparison of optimal results for the second load level of test system II.

Method	P_1	P_2	P_3	P_4	H_2	H_3	H_4	H_5	$\sum P$	$\sum H$	Total Cost
HS [6]	134.67	52.99	10.11	52.23	85.69	39.73	4.18	45.40	250	175	12284.45
GA [6]	119.22	45.12	15.82	69.89	78.94	22.63	18.40	54.99	250.05	174.96	12327.37
EDHS* [7]	135	0.1112	0	114.8888	85.8178	56.3198	0	32.8135	250	174.9511	11836.00
TVAC-PSO [15]	135.000	40.012	10.039	64.949	74.826	39.844	16.187	44.143	250.00	175.000	12117.389
Proposed	135	40.48	10	64.51	75.35	40	14.93	44.73	250	175	**12121.5575**

*Not feasible

Table 9. Comparison of optimal results for the third load level of test system II.

Method	P_1	P_2	P_3	P_4	H_2	H_3	H_4	H_5	$\sum P$	$\sum H$	Total Cost
HS [6]	41.41	66.61	10.59	41.39	97.73	40.23	22.83	59.21	160	220	11810.88
GA [6]	37.98	76.39	10.41	35.03	106	38.37	15.84	59.97	159.81	220.18	11837.40
EDHS* [7]	135	0	0	25	87.2560	58.1586	40.1823	34.3703	160	219.9672	93181
TVAC-PSO [15]	42.143	64.627	10.000	43.229	96.259	40.001	23.740	60.000	160.00	220.000	11758.062
Proposed	46.02	68.95	10.03	35	99.99	40.01	20	60	160	220	**11766.4369**

*Not feasible

capacity of them are incorporated in the formulation. The results are compared with the results of the other optimization methods such as genetic algorithm, harmonic search, particle swam optimization and ant colony algorithm, which demonstrate the dominance of the proposed method in finding the solutions with the lowest costs and respecting all problem constraints.

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