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Economic Dispatch of Combined Heat and Power Systems using Particle Swarm Optimization

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ABSTRACT

Due to the limitations and high cost of fossil fuel energy sources, combined heat and power units (CHPs) are gaining more attention recently as they are more efficient and less pollutant than conventional sources. In order to use CHP units more efficiently, the economic dispatch problem (EDP) is applied to obtain the optimal power and heat sources' outputs to satisfy heat and power demands while meeting the different operational constraints. The problem is nonlinear and non-convex which requires heuristic technique to be used to solve this complex problem. Particle Swarm Optimization (PSO) is utilized due to its effectiveness in solving complex problems due to its high convergence speed with less number of iterations. The EDP main objective is to obtain optimal output power and heat of each unit while the total generation cost is minimized. The obtained results justify the superiority of the proposed method in solving such complicated problems.

Keywords: combined heat and power, particle swarm optimization, economic dispatch

1 INTRODUCTION

Combined heat and power (CHP) sources of energy have a wide spread utilization recently. CHPs can supply both power and heat demands simultaneously. CHPs can provide higher efficiency than conventional power-only generating units with less gas emissions by almost 13–18% [1]. The efficiency of CHP units is around 90% , while it is less than 60% for other combined cycle power plants [2].Furthermore, CHPs show a significant improvement in cost saving of typical 10–40% [3].

Economic dispatch problem aims at minimizing the total operation costs while finding the optimal dispatch of three types of generating units. Heat-only, power-only and CHP units are the three types of generating units in a cogeneration system. In combined heat and power economic dispatch problem, two types of loads are satisfied comprising power and heat loads. The generated power in CHP units relies on the generated heat and vice versa which results in a more complex problem [4]. Existence of CHP units in the EDP makes the problem more complicated as it is converted to a nonlinear and non-convex problem due to the dual dependency between power and heat production.

Recently, many works tried to solve the EDP of CHP units using evolutionary and heuristic techniques. In [5], an effective cuckoo search algorithm is developed to search for the optimal solutions to the EDP of CHP units. While in [6], a modified group search optimizer (MGSO) algorithm is proposed for solving the combined heat and power economic dispatch problem with bounded feasible operating region. MGSO is a population-based optimization algorithm inspired by group-living animal territory. While Group search optimization (GSO) method that is based on searching behavior of animals, is presented in solving EDP of CHP units in [7].Whereas in [8], opposition-based group search optimization to solve non-smooth non-convex combined heat and power economic dispatch problem is presented. Valve-point loading and prohibited operating zones of conventional thermal generators are considered. While the authors of [9] proposed an integrated technique that embeds civilized swarm optimization (CSO) and Powell’s pattern search (PPS) method to search economic dispatch of CHP dispatch problem. In the proposed technique, CSO is selected as global search technique and PPS is undertaken as a local search technique. In [10], EDP is proposed in grid-connected and heat network-connected CHP microgrids with storage systems and responsive loads considering reliability and uncertainties. While in [11], district energy system modeling and optimal operation considering CHP units with dynamic response to wind power ramp events is conducted. In [12], operation optimization on the large-scale CHP station composed of multiple CHP units and a thermocline heat storage tank is presented. Whereas in [13], operation scheduling of a coal-fired CHP station integrated with power-to-heat devices with detail CHP unit models is solved by particle swarm optimization algorithm. While in [14], probabilistic optimal coordinated planning of molten carbonate fuel cell CHP and renewable energy sources in microgrids is performed considering hydrogen storage with point estimate method.

2 The Economic Dispatch Problem Formulation

In the ED of a power system comprising CHP units there are three types of generating units, power only, heat only, and CHP units. The objective function aims at minimizing the total generation costs of the three types of units while satisfying the operational constraints. The fuel cost of a power only unit depends on its electricity generation level. Similarly, the operating costs of CHP units depend on the amount of heat and electricity they generate. Additionally, CHP units have a feasible operating region that lie within some limits for power and heat that they can generate. An example for heat-power operating region for a CHP unit is presented in Fig.1. The problem objective function (OF) is given as follows:

$$\textbf{Min OF} = \sum_{i=1}^{Np} f_i(P_i^p) + \sum_{j=1}^{Nc} f_j(P_j^c, H_j^c) + \sum_{m=1}^{N_h} f_m(H_m^h) \qquad \textbf{(1)}$$

Where $f_i(P_i^p)$ is the operation cost of ith power-only unit for generating P_i^p MW. While the operation cost for jth CHP unit is denoted by $f_j(P_j^c, H_j^c)$ for generating P_j^c MW electricity power and H_j^c MWth heat power. Whereas $f_m(H_m^h)$ is the operation cost of heat-only unit when generating H_m^h MWth heat power. N_p, N_c and N_h are the total numbers of power-only, CHP and heat-only units, respectively. i, j and m are indices for above mentioned units, respectively. Cost functions of units are formulated as:

$$f_i(P_i^p) = a_i(P_i^p)^2 + b_i(P_i^p) + c_i \qquad (2)$$

$$f_j(P_j^c, H_j^c) = a_j(P_j^c)^2 + b_j(P_j^c) + c_j + d_j(H_j^c)^2 + e_j(H_j^c) + f_j\, P_j^c\, H_j^c \qquad (3)$$

$$f_m(H_m^h) = a_m(H_m^h)^2 + b_m(H_m^h) + c_m \qquad (4)$$

Where a_i, b_i, c_i are the constant cost coefficients of the power only units. Whereas a_j, b_j, c_j, d_j, e_j, f_j are the cost coefficients for CHP units while a_m, b_m, c_m are the cost coefficients for heat only units.

The problem constraints are as follows:

The summation of the generated power should meet the required power and heat demands plus the transmission power losses.

$$\sum_{i=1}^{N_p} P_i^p + \sum_{j=1}^{N_c} P_j^c = P_l + P_{loss} \qquad (5)$$

$$\sum_{j=1}^{N_c} H_j^c + \sum_{m=1}^{N_h} H_m^h = H_l \qquad (6)$$

Where P_l and H_l are the power demand and heat demand respectively. P_{loss} is the power losses in transmission. The generated power and heat should lie within upper and lower limits of the various generating unit types as follows:

$$\boldsymbol{P_i^{p,min} \le P_i^p \le P_i^{p,max} \ , \forall \, i \, \epsilon \, N_p} \quad (7)$$

$$\boldsymbol{P_j^{c,min}(H_j^c) \le P_j^c \le P_j^{c,max}(H_j^c) \ , \forall \, j \, \epsilon \, N_c} \quad (8)$$

$$\boldsymbol{H_j^{c,min}(P_j^c) \le H_j^c \le H_j^{c,max}(P_j^c) \ , \forall \, j \, \epsilon \, N_c} \quad (9)$$

$$\boldsymbol{H_m^{h,min} \le H_m^h \le H_m^{h,max} \ , \forall \, m \, \epsilon \, N_h} \quad (10)$$

Where $P_i^{p,max}$ and $P_i^{p,min}$ are the maximum and minimum power generation bounds for the power only units while$P_j^{c,max}$, $P_j^{c,min}$, $H_j^{c,max}$, $H_j^{c,min}$ are the power maximum and minimum limits and the heat maximum and minimum limits for CHP units. Similarly for heat only units $\boldsymbol{H_m^{h,max}}$, $\boldsymbol{H_m^{h,min}}$ are their maximum and minimum generated heat limits.

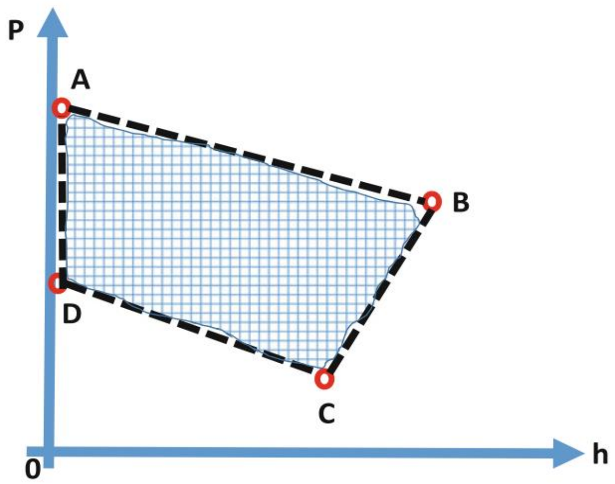

Fig.1. power-heat feasible operating region for a CHP generating unit

3 Particle Swarm optimization

Particle Swarm Optimization (PSO) is first introduced by Kennedy and Eberhart in 1995 [15]. It is an optimization algorithm that relies on swarm intelligence inspired by swarm behavior of birds and fish schools. This algorithm randomly initializes the particle population and then converges to the optimal value through some iteration. In PSO, the decision variables are the positions of particles. Each particle *i* has a position vector *Y* and a speed vector *U* in each iteration number *iter* which may be expressed as:

$$\boldsymbol{Y_i^{iter}} = [\boldsymbol{y_{i,1}^{iter}}, \ \boldsymbol{y_{i,2}^{iter}}, \dots \dots .., \boldsymbol{y_{i,N}^{iter}}] \quad (11)$$

$$\boldsymbol{U_i^{iter}} = [\boldsymbol{u_{i,1}^{iter}}, \ \boldsymbol{u_{i,2}^{iter}}, \dots \dots .., \boldsymbol{u_{i,N}^{iter}}] \quad (12)$$

Where *N* is the total number of decision variables in the ED problem. Each particle in each iteration will seek for a better position utilizing its current speed, its own experience of previous iterations and other particles' experiences. The mathematical expressions of this process are as follows:

$$u_{i,n}^{iter} = \omega\, u_{i,n}^{iter-1} + c_1\, r_1^n\, (p_{best_{i,n}}^{iter-1} - y_{i,n}^{iter-1}) + c_2\, r_1^n\, (g_{best_{i,n}}^{iter-1} - y_{i,n}^{iter-1}) \quad (13)$$

$$y_{i,n}^{iter} = y_{i,n}^{iter-1} + u_{i,n}^{iter} \quad (14)$$

Where ω is the inertia weight, C_1 and C_2 are learning factors, r_1^n and r_1^n are random numbers in the interval [0, 1]. $p_{best_{i,n}}^{iter-1}$ and $g_{best_{i,n}}^{iter-1}$ are the best positions of ith particle in previous iteration and the best position of entire swarm, respectively. The updated speeds should lie within a certain bounds:

$$-u_n^{max} \leq u_{i,n} \leq u_n^{max} \quad (15)$$

$$u_{i,n}^{max} = \frac{y_n^{max} - y_n^{min}}{z} \quad (16)$$

where y_n^{max}, y_n^{min} are the maximum and minimum bounds of variables as described in (7–10). Z *is* a parameter controls how the speed is changed. A flowchart of the PSO algorithm and how it is applied to the ED problem of CHPs is presented in Fig.2.

4 Results and Discussions

The ED problem is applied to a power system consisting of two power-only units, two CHP units and two heat-only units to minimize the total generation costs while satisfying the various operational constraints. The data for the various energy sources is shown in Table.1. The feasible operating regions for the CHP units are depicted in Table.2. The electric and heat demands are assumed to be 605 MW and 540 MW, respectively. The transmission losses are assumed to be zero for simplicity.

Table.1.The data for the various energy sources

Technology	*a*	*b*	*c*	*d*	*e*	*f*	P^{min}	P^{max}	h^{min}	h^{max}
*g*1	3.00	20.00	100.00				30.00	180.00		
*g*2	4.05	18.07	98.87				90.00	290.00		
*h*1	4.05	10.55	104.26						60.00	200.00
*h*2	3.99	9.21	107.21						70.00	270.00
chp1	0.0345	14.00	2540.00	0.03	4.20	0.031				
chp2	0.0435	13.00	1460.00	0.02	0.70	0.011				

Table.2 The feasible operating regions for the CHP units

CHP unit	Aq	Ap	Bq	Bp	Cq	Cp	Dq	Dp
chp1	0	247	180	215	104.8	81	0	99
chp2	0	125	135	110	75	40	0	45

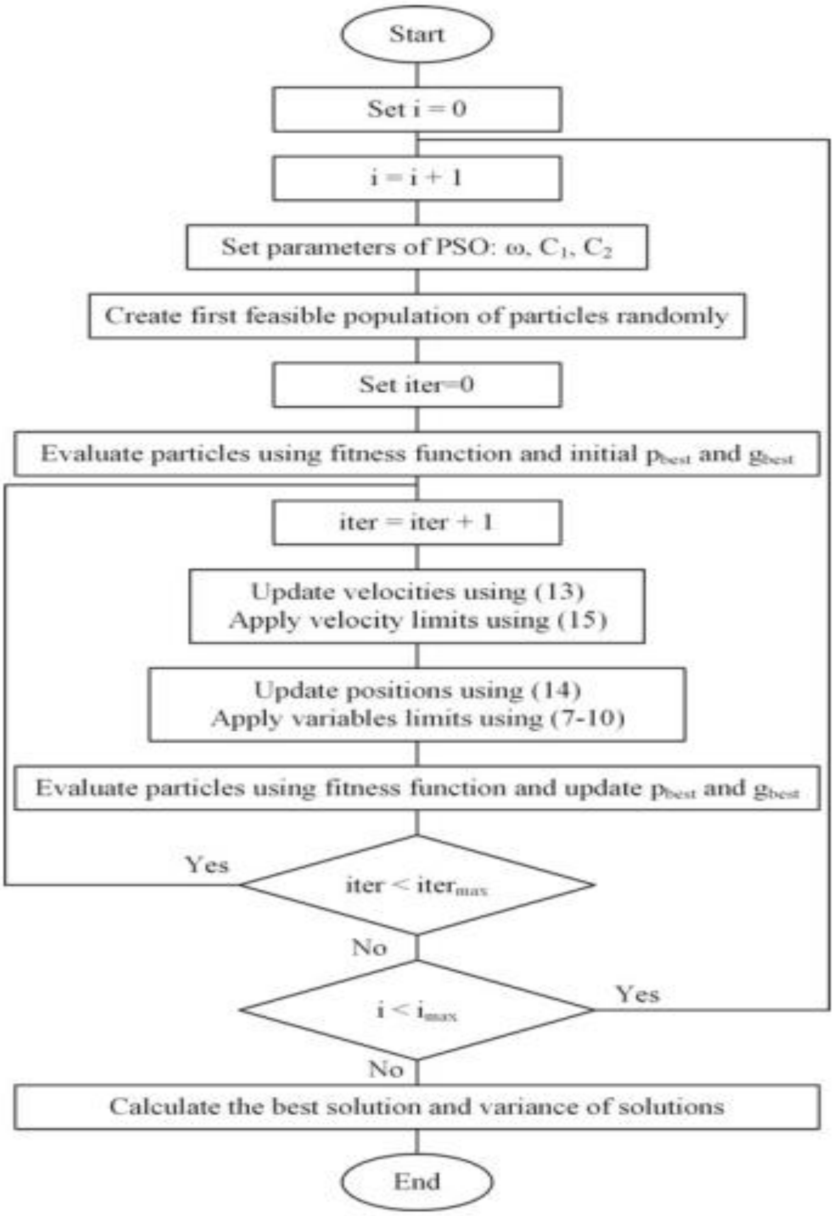

Fig.2. A flowchart of the PSO algorithm and its application to the ED problem of CHPs

The PSO algorithm is implemented with the help of MATLAB software to be applied to the problem. In order to investigate the random nature of evolutionary algorithms, the proposed method is performed for 100 times and the variations of solutions are displayed in Fig. 3. The total operation costs are 245,591.162 \$/h (F^{th} =1.4 x 10^5 \$/h, F^{h} =1.0418 x 10^5 \$/h, F^{chp} =14,111.162 \$/h). It should be noted that 52.34 s elapsed for 100 runs of the program. The best solution for the different technologies is reported in Table 3. Also, the convergence of PSO method for the best solution is depicted in Fig. 4.

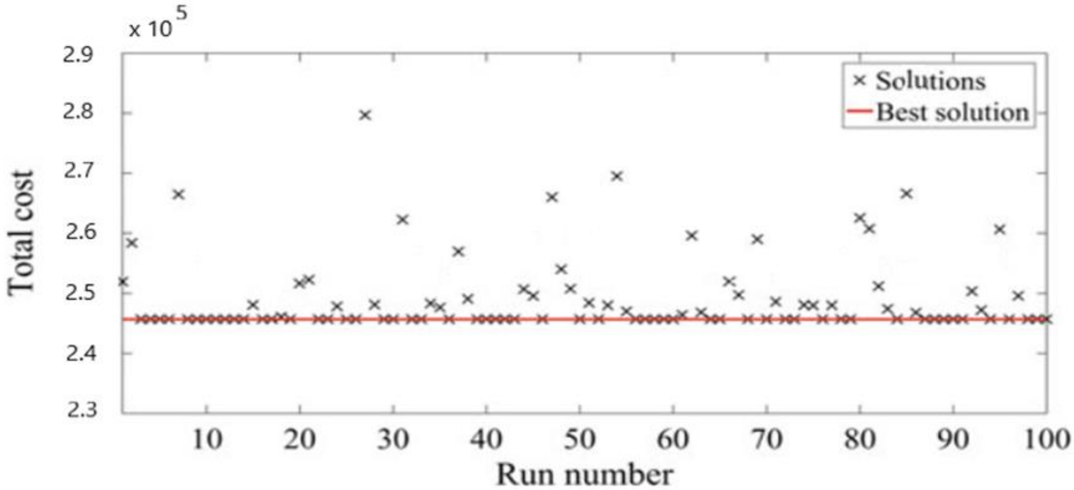

Fig.3 Variations of solutions for different runs of program

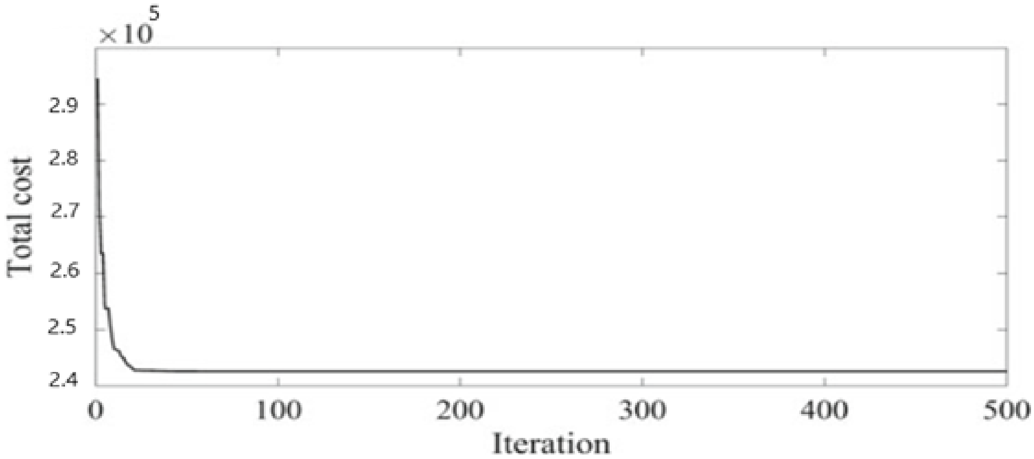

Fig. 4. The convergence of PSO method for the best solution

Table 3. The best solution for the different technologies

Technology	p	Technology	q
chp1	215	chp1	180
chp2	110	chp2	135
$g1$	160.714	$h1$	111.577
$g2$	119.286	$h2$	113.423
L_e	605	L_h	540

5 CONCLUSIONS

The modern power systems require more efficiency and less pollution. CHP units can supply both electric power and heat demand simultaneously with less power losses and emissions than conventional fossil fuel sources. However, CHP units have nonlinear and non-convex characteristics which add more complexity in the ED problem solving which aims at minimizing the total operational costs. Thus, heuristic and evolutionary algorithms become more common due to their higher speed and better results. In this work the combined heat and power economic dispatch problem, as a simple application of evolutionary algorithms in power systems, is solved using PSO in MATLAB software. PSO is used to solve the economic dispatch problem of CHP units which is a non-convex and nonlinear optimization problem that is hard to solve with classical optimization algorithms. Results show the good performance and the fast convergence of the PSO algorithm in solving such nonlinear problem.

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