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Environmental Constrained Combined Heat and Power Dispatch using a Grey Wolf Algorithm

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Abstract: The purpose of this paper is to obtain the best feasible solution for Combined Heat and Power Dispatch (CHPD) problems. Being inspired by the hunting and searching behaviours of grey wolves, a swarm intelligence algorithm, Grey Wolf Algorithm (GWA) has been developed and is used as an optimization tool for the chosen problem. In addition to the non-linear and non-convex operational characteristics of generating units, the practical operational constraints such as feasible operating regions of cogenerators, valve point effect of thermal generators are considered. The GWA is implemented on the standard test systems for economic and combined economic emission dispatch operations. The obtained results are higher feasible than or as well as the best known solutions by state-of-the-art algorithms reported in the literature. It is evident that the GWA attains a higher quality solution to CHPD problems.

Keywords: Combined Heat and Power System, Economic Dispatch, Emission Dispatch, Grey Wolf Algorithm

I. INTRODUCTION

Combined Heat and Power (CHP) - an integrated system that simultaneously generates electricity and useful heat from a single fuel-is a versatile technology that can generate useful energy more efficiently, and thereby significantly and economically improve energy efficiency and deliver substantial benefits for end-user facilities, utilities, and communities. As the society needs heat and power, combined heat and power generation is environmentally and economically advantageous. Currently, the environmental related issues are becoming more pronounced as the number of thermal generating plants that uses fossil fuel are increasing, hence the emissions resulting in power production from these plants are polluting the environment that enhance the greenhouse gases emissions. Therefore, it is very important for optimizing both the generation cost as well as the cost associated with the control of emissions from CHP unit operation. Hence, a new optimal operation model of CHP plants has been developed by considering environmental and economic perspectives. The objective of Economic Emission Dispatch of Combined Heat and Power (EED-CHP) plant is to find the optimal point of power and heat generation with minimum fuel cost such that both heat and power demand and other constraints are met while cogenerating units are operated in a bounded heat versus power plane.

I. Review of existing methods

Incorporating cogeneration units into the existing utility makes economic dispatch problem further complexity to the solution methodology. Several classical optimization techniques, such as direct search method [1], mesh adaptive direct search algorithm [2] and Lagrangian relaxation [3, 4] have been used to solve the Combined Heat and Power Economic Dispatch (CHPED) problem. These techniques need approximations that lead to local optimal solution. The stochastic search algorithms have provided alternative approaches for

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solving CHPED problem. Recently, Evolutionary Programming (EP) [5], Differential Evolution (DE) [6], Genetic Algorithm (GA) [7], Harmony Search (HS) algorithm [8,9], Benders Decomposition (BD) [10], Self Adaptive Real Coded Genetic algorithm (SARGA) [11], Non dominated Sorting Genetic Algorithm (NSGA) [12], Particle Swarm Optimization (PSO) [13], Bee colony algorithm [14], Harmony Search-Genetic Algorithm (HSGA) [15] and Canonical Coordinates Method (CCM) [16] have been suggested for solving CHPED problem. Charged System Search Algorithm (CSSA) [17] and Time Varying Acceleration Coefficients PSO (TVAC-PSO) [18] have also been applied to solve CHPED problem considering valve-point effects of thermal generators. Mehrdad Tarafdar Haghet al., [19] presented an Improved Group Search Optimization (IGSO) algorithm for solving CHPED problem in large scale power systems.

II. **GWA as an optimization tool**

A bio-inspired optimization algorithm developed by Mirjalili et al., [20], the so called Grey Wolf Algorithm (GWA), mimics the leadership hierarchy and hunting mechanism of grey wolves in nature. This algorithm has few parameters and easy to implement, which makes it superior than earlier ones. The GWA is effectively proposed in CHPD problems. The proposed method is tested on different scale of test systems. The obtained results are compared with the earlier reports and GWA emerges out to be a stout optimization technique for solving CHPD problem for linear and nonlinear models.

2. PROBLEM FORMULATION OF EED-CHP

Conventional power only unit, combined heat and power units (Cogeneration units) and heat only units are considered in this study. The CHP system's total cost (1) can be mathematically represented in the following form.

$$Minimize\ \ C_T = \sum_{i=1}^{Np} C_p(P_i) + \sum_{j=1}^{Nc} C_c(P_{cj}, H_{cj}) + \sum_{k=1}^{Nh} C_h(H_k) + [\sum_{i=1}^{Np} E_p(P_i) + \sum_{j=1}^{Nc} E_c(P_{cj}, H_{cj}) + \sum_{k=1}^{Nh} E_h(H_k)]\ \ (\$/h) \quad (1)$$

i.e. (1) is expanded as follows

$$C_T = \begin{bmatrix} \underbrace{\sum_{i=1}^{Np} a_i + b_i P_i + c_i P_i^2 + \left| e_i \sin(f_i(P_i^{\min} - P_i)) \right|}_{Power\ \ only\ \ units} + \\ \underbrace{\sum_{j=1}^{Nc} \alpha_j + \beta_j P_{cj} + \gamma_j P_{cj}^2 + \varepsilon_j H_{cj} + \eta_j H_{cj}^2 + \phi_j P_{cj} H_{cj}}_{Cogeneration\ \ units} + \\ \underbrace{\sum_{k=1}^{Nh} \varphi_k + \lambda_k H_k + \mu_k H_k^2}_{Heat\ \ only\ \ units} \end{bmatrix} + \begin{bmatrix} \underbrace{\sum_{i=1}^{Np} \varpi_i + \sigma_i P_i + \psi_i P_i^2 + \tau_i e(\theta_i P_i)}_{Power\ \ only\ \ units} + \\ \underbrace{\sum_{j=1}^{Nc} \xi_j P_{cj}}_{Cogeneration\ \ units} + \\ \underbrace{\sum_{k=1}^{Nh} \vartheta_k H_k}_{Heat\ \ only\ \ units} \end{bmatrix} (\$/h) \quad (2)$$

Subject to the constraints of electricity (3), cogeneration, heat production (4) and the operating limits (5)-(8) of each unit.

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Power generation and demand balance

$$\sum_{i=1}^{Np} P_i + \sum_{j=1}^{Nc} P_{cj} = P_d \qquad \text{(MW)} \tag{3}$$

Heat generation and demand balance

$$\sum_{j=1}^{Nc} H_{cj} + \sum_{k=1}^{Nh} H_k = H_d \qquad \text{(MWth)} \tag{4}$$

Operating limits

$$P_i^{\min} \le P_i \le P_i^{\max} \qquad i = 1,\dots\dots, Np \tag{5}$$

$$P_{cj}^{\min}(H_{cj}) \le P_{cj} \le P_{cj}^{\max}(H_{cj}) \qquad j = 1,\dots\dots, Nc \tag{6}$$

$$H_{cj}^{\min}(P_{cj}) \le H_{cj} \le H_{cj}^{\max}(P_{cj}) \qquad j = 1,\dots\dots, Nc \tag{7}$$

$$H_k^{\min} \le H_k \le H_k^{\max} \qquad i = 1,\dots\dots, Np \tag{8}$$

Feasible operating region constraints - In the heat-power feasible operation region Figure 1 of a combined cycle co-generation unit, the power outputs and heat outputs are restricted by their own upper and lower limits, and in some cases changing one would affect the other.

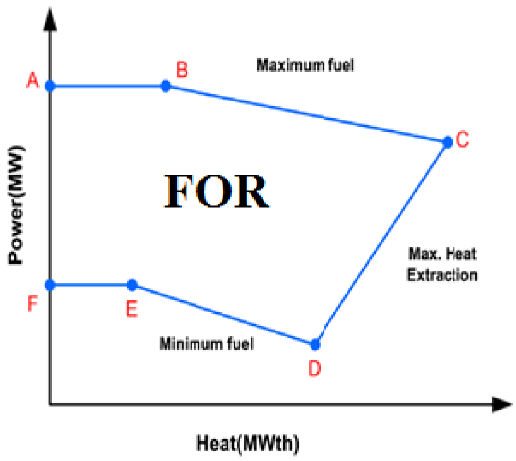

Figure 1 Heat-power feasible operating region for a cogeneration unit

II. Grey Wolf Algorithm (GWA)

The GWA mimics the hunting behavior and the social hierarchy of grey wolves. In the societal hierarchy, grey wolves are categorized as alpha (α), beta (β), delta (δ) and omega (ω). The alphas are the dominant because the group follows his/her instructions and the betas; the secondary wolves assist the alphas in making decisions. Omega is the lowest ranking grey wolves. If a wolf is neither an alpha nor a beta, or an omega, he/she is called delta (sub-ordinate). Delta wolves come in the hierarchy next to the alphas and betas but they

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lead the omega. In addition to the social hierarchy of wolves, group hunting is another appealing societal action of grey wolves. The main segments of GWA are encircling, hunting and attacking the prey.

I. Social hierarchy

The fitness solutions are structured according to the societal hierarchy of wolves. The best fitness solution is regarded as alpha followed by beta, delta and omega wolves.

II. Encircling prey

A grey wolf can update its position inside the space around the prey in any random location by using Eqs. (9) and (10).
The encircling behavior of grey wolves can be represented as:

$$\vec{D} = \left| \vec{C} . \vec{X}_p(t) - \vec{X}(t) \right| \tag{9}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}. \vec{D} \tag{10}$$

Where, $\vec{D}$, $\vec{X}$ and $\vec{X}_P$ indicates the direction, position vector for grey wolf and position vector of prey. The vectors values of $\vec{A}$ and $\vec{C}$ are computed using the following equations:

$$\vec{A}. = 2\vec{a}.rand_1 - \vec{a} \tag{11}$$

$$\vec{C}. = 2.rand_2 \tag{12}$$

The components of $\vec{a}$ are linearly decreased from 2 to 0 over the course of iterations.

III. Hunting

The alpha, beta and delta type grey wolves have superior knowledge about the potential location of prey. Hence, the first three best solutions acquired are saved and coerce the other search agents to update their positions according to the location of the best search agents. The following equations can be used in this regard.

$$\vec{D}_\alpha = \left| \vec{C}_1 . \vec{X}_\alpha - \vec{X} \right| \tag{13}$$

$$\vec{D}_\beta = \left| \vec{C}_2 . \vec{X}_\beta - \vec{X} \right| \tag{14}$$

$$\vec{D}_\delta = \left| \vec{C}_3 . \vec{X}_\delta - \vec{X} \right| \tag{15}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 . (\vec{D}_\alpha) \tag{16}$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 . (\vec{D}_\beta) \tag{17}$$

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$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3.\ (\vec{D}_\delta) \tag{18}$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \tag{19}$$

IV. Attaching the prey

In this phase, the value of $\vec{a}$ is reduced and thereby the fluctuation range of $\vec{A}$ is decreased. When $\vec{A}$ has random values in the range [-1, 1], then the search agent's next location will be in any place between its current position and the position of the prey.

V. Exploration

Grey wolves mostly search according to the position of the alpha, beta, and delta. They diverge from each other to search for prey and converge to attack prey. In order to mathematically model divergence, we utilize $\vec{A}$ with random values greater than 1 or less than -1 to oblige the search agent to diverge from the prey. This emphasizes exploration and allows the GWA algorithm to search globally.

3. EXECUTION PROCESS FOR EED-CHP-GWA

GWA has been implemented for solving EED-CHP problem and the stepwise procedure is as follows.

Step 1: Define EED- CHP problem as a minimization problem.

$$Minimize C(PH) \tag{20}$$

Where C (PH) is the objective function, and PH = Dp, Dpc, Dhc, Dh are vector of decision variables generated between the maximum and minimum operating limits.

Step 2: Read the system data and initialize GWA parameters such as maximum number of iterations (iter) and the vectors value (a, A and C) using the Eqs. (11) – (12).

Step 3: Initialization of population with random generation using (21) and evaluate them.

$$\text{Population} = \begin{bmatrix} P_1^1..P^1{}_{Dp} & P_c^1..P_c^1{}_{D_{pc}} & H_c{}^1..H_c{}^1{}_{D_{hc}} & H_1^1..H^1{}_{D_h} \\ P_1^2..P^2{}_{Dp} & P_c^2..P_c^2{}_{D_{pc}} & H_c{}^2..H_c{}^2{}_{D_{hc}} & H_1^2..H^2{}_{D_h} \\ \dots\dots & \dots\dots & \dots\dots & \dots\dots \\ P_1^{Ps-1}..P^{Ps-1}{}_{Dp} & P_c^{Ps-1}..P_c^{Ps-1}{}_{D_{pc}} & H_c{}^{Ps-1}..H_c{}^{Ps-1}{}_{D_{hc}} & H_1^{Ps-1}..H^{Ps-1}{}_{D_h} \\ P_1^{Ps}..P^{Ps}{}_{Dp} & P_c^{Ps}..P_c^{Ps}{}_{D_{pc}} & H_c{}^{Ps}..H_c{}^{Ps}{}_{D_{hc}} & H_1^{Ps}..H^{Ps}{}_{D_h} \end{bmatrix} \begin{matrix} \to & C(PH^1) \\ \to & C(PH^2) \\ \to & \dots.. \\ \to & C(PH^{Ps-1}) \\ \to & C(PH^{Ps}) \end{matrix} \tag{21}$$

Step 4: Compute the fitness C (PH) of each individual, an individual having the minimum fitness (i.e. C (PH) min) is mimicked as the alpha, second minimum is beta and third minimum is delta.

$$(PH\alpha) = C\ (PH)\ 1 \quad \text{where } C\ (PH)\ 1 \ = C\ (PH)\ \min \tag{22}$$
$$(PH\beta) = C\ (PH)\ 2 \quad \text{where } C\ (PH)\ 2 \ = C\ (PH)\ \min+1 \tag{23}$$
$$(PH\delta) = C\ (PH)\ 3 \quad \text{where } C\ (PH)\ 3 \ = C\ (PH)\ \min+2 \tag{24}$$

Step 5: Update the position of wolves (PHα, PHβ, PHδ) through hunting using Eqs. (13) – (19).

Step 6: Update the vector values of (a, A and C).

Step 7: Compute the fitness C (PH) and find the new values (PHα, PHβ, PHδ).

Step 8: Termination criterion

Repeat the procedure from steps 5 to 7 until the maximum number of iteration is reached.

4. VERIFICATION VIA TEST SYSTEMS

This section details the performance of GWA in solving various types of CHPD problems. The proposed method has been implemented on the standard test systems comprise of 4 unit and 7 units. The program has been written in MATLAB-7.9 language and executed on a 2.3 GHz Intel core i3 personal computer with 4 GB RAM. The obtained simulation results are compared with the recent reports in term of solution quality.

I. **Test system I:** CHP considering Economic Dispatch

Guo et al. (1996) proposed this system, consists four units in which two are cogeneration units and one power-only and heat-only unit [2]. The linear functions are used to model the operational characteristics of power and heat-only units and the co-generator is represented as a second-order function of its power and heat outputs. For the sake of simplicity, valve-point effects and transmission loss are neglected. The economic dispatch is carried out for the power demand of 200 MW and head demand of 115MWth.

Table 1: CHP dispatch results for 4-unit test system and comparison with other algorithms (P_d=200MW and H_d= 115MWth)

Methods	**Power Output (MW)**			**Heat Output (MWth)**			**P_d (MW)**	**H_d (MWth)**	**Cost ($/h)**
	P_1	**P_2**	**P_3**	**H_2**	**H_3**	**H_4**			
IACS	0.08	150.93	49	48.84	65.79	0.37	200.1	115	9452.2
GA-PF	0	159.23	40.77	39.94	75.06	0	200	115	9267.28
PSO	0.05	159.43	40.57	39.97	75.03	0	200.05	115	9265.1
IGA	0	160	40	39.99	75	0	200	114.99	9257.09
CPSO	0	160	40	40	75	0	200	115	9257.08
SARGA	0	159.99	40.01	39.99	75	0	200	114.99	9257.07
HS	0	160	40	40	75	0	200	115	9257.07
TVAC-PSO	0	160	40	40	75	0	200	115	9257.07
EDHS	0	200	0	0	115	0	200	115	8606.07*
SPSO	0	159.706	39.909	40	75	0	199.6162	115	9248.17*

OTLBO	0	160	40	40	75	0	200	115	9257.07
GWA	**0**	**160**	**40**	**40**	**75**	**0**	**200**	**115**	**9257.07**

* Not feasible

The optimal dispatches obtained by the proposed algorithm are presented in the Table 1. The total cost attained by the GWA for the abovementioned demands is $ 9257.07. A comparison in terms of minimum fuel cost has been made with the earlier reports. The proposed method has close agreement with other methods except EDHS and SPSO. These two methods cannot be directly compared because their solutions are infeasible. Referring from the FOR of CHP unit 2, the minimum real power generation is about 40 MW but EDHS attains no real power generation, this make the heat and power dispatches fall out of the feasible operating region, thus solution is infeasible. SPSO provides a real power mismatch of around 0.4 MW that leads to show the less fuel cost.

II. Test system-II: CHP considering Environmental Constraints

The test system chosen for simulation comprises of four power-only units, two cogeneration units and a heat-only unit. The quadratic expressions are adopted to depict the units' characteristics excluding the emission characteristics of cogenerators and heat-only units which are expressed as linear functions. The test system details are available in the literature (Basu, 2013). The valve-point loading effects in power-only units and network loss are considered. The prescribed power and heat demands are 600 MW and 150 MWth respectively.

Table 2: Economic and Emission Dispatch and Comparison with Existing Methods for7-unit Test System

Objectives	**Economic Dispatch**		**Emission Dispatch**	
Methods / **Output**	RCGA	**GWA**	RCGA	**GWA**
P1(MW)	74.5357	**52.7473**	73.3318	**51.1917**
P2	99.3518	**98.5398**	81.0489	**54.610**
P3	174.7196	**112.6734**	93.4210	**60.9319**
P4	211.0170	**209.8359**	125.2112	**86.3858**
P5	100.9363	**93.7515**	214.9958	**244.3999**
P6	44.1036	**40.000**	125.7907	**110.1999**
H5 (MWth)	24.3678	**29.4104**	104.7715	**14.3999**
H6	72.5270	**75.0000**	31.9272	**135.5908**
H7	53.1052	**45.5895**	13.3013	**0**
Ploss (MW)	NR	**7.5505**	NR	**7.6902**
Cost ($/h)	10712.86	**10110.14**	17749.31	**17278.15**
Emission (kg/h)	39.5749	**28.1809**	16.9208	**8.0785**
CPU time (s)	20.3438	**3.523**	22.7813	**3.523**

NR-Not Reported in the Literature

From Table 2, GWA attains $10110.14/h and 28.1809kg/h for cost minimization and $17278.15/h and 8.0785kg/h for emission minimization. The RCGA (Basu, 2013) has been reported $10712.86/h and

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39.5749kg/h for economic dispatch and $17749.31/h and 16.9208kg/h for emission dispatch. Comparing with RCGA, the GWA provides the best feasible solution for individual optimization cases.

Table 3: Combined Economic Emission Dispatch Results and Comparison with Existing Methods for 7-unit Test System

Objectives	**Economic Emission Dispatch**		
Methods / **Output**	SPEA 2	NSGA-II	**GWA**
P1(MW)	73.3149	73.5896	**66.6968**
P2	117.7996	106.8761	**97.4845**
P3	117.7996	119.0311	**96.4885**
P4	151.6436	163.5563	**114.8909**
P5	195.1355	188.4166	**191.999**
P6	54.0988	58.4850	**40.000**
H5 (MWth)	25.8784	26.8054	**5.7027**
H6	75.5331	73.9970	**75.000**
H7	48.5884	49.1976	**69.2973**
Ploss (MW)	NR	NR	**5.5799**
Cost ($/h)	13448.95	13433.19	**12393.06**
Emission (kg/h)	25.7810	25.8262	**17.3225**
CPU time (s)	53.4688	9.7188	**3.523**

NR-Not Reported in the Literature

Initially, the total production cost and total emission are independently minimized subject to the system operation constraints and Weighted Aggregation (WA) method is employed to blend both economic and emission objectives. The best feasible solutions for all cases obtained using GWA and the numerical results comparisons are presented in the Table 2. Further, the GWA algorithm is applied for determining the best compromise dispatch while considering cost and emission objectives. From Table 3, the total fuel cost and emission are found to be $12393.06/h and 17.3225kg/h using the GWA which is the best compromised solution as compared with the earlier reports (SPEA 2 and NSGA-II).

III. Weighted Aggregation Method

A multi-objective optimization task involving multiple conflicting objectives of demands finding a multi-dimensional Pareto-optimal front. For a multi-objective optimization problem, there does not exist a single solution that simultaneously optimizes each objective. In that case, the objective functions are said to be conflicting, and there exists a number of Pareto optimal solutions. A solution is called non dominated, Pareto optimal, Pareto efficient, if none of the objective functions can be improved in value without degrading some of the other objective values. Without additional subjective preference information, all Pareto optimal solutions are considered equally good.

In this work, a weighted aggregation method is employed to optimize the operational objectives simultaneously. The WA method scalarizes a set of objectives into a single objective by pre-multiplying each objective with a user-specified weight. The weight of each objective is usually selected in proportion to its relative importance in the overall problem. When such objectives are weighted to form a single aggregated objective function, quite often they need to be scaled appropriately in order to fall into the identical order of magnitude. After the objectives are normalized, an aggregated objective function can be formed by summing up the weighted normalized objectives. In practice, the sums of the weights for different objectives are usually chosen as one. Thus, the CHP system economic emission problem is converted into a single-objective optimization problem as follows:

$$\text{Minimize } WF\,(PH) + (1 - W)\,\lambda E\,(PH) \tag{25}$$

In the simulations, the weight W varies within [0, 1], and the scaling factor λ is chosen as 3500 in order to treat the objectives (fuel cost and emission) equally.

Figure 2 shows the Pareto-optimal of GWA for 7-unit systems. It should be noted that, to obtain the Pareto fronts, the simulation needs to run multiple times by varying the weight between 0 and 1. The overall operating cost and the compromised solution attained by GWA is superior for multi-objective optimization problems; it shows its ability to attain the global minimum in a reliable manner.

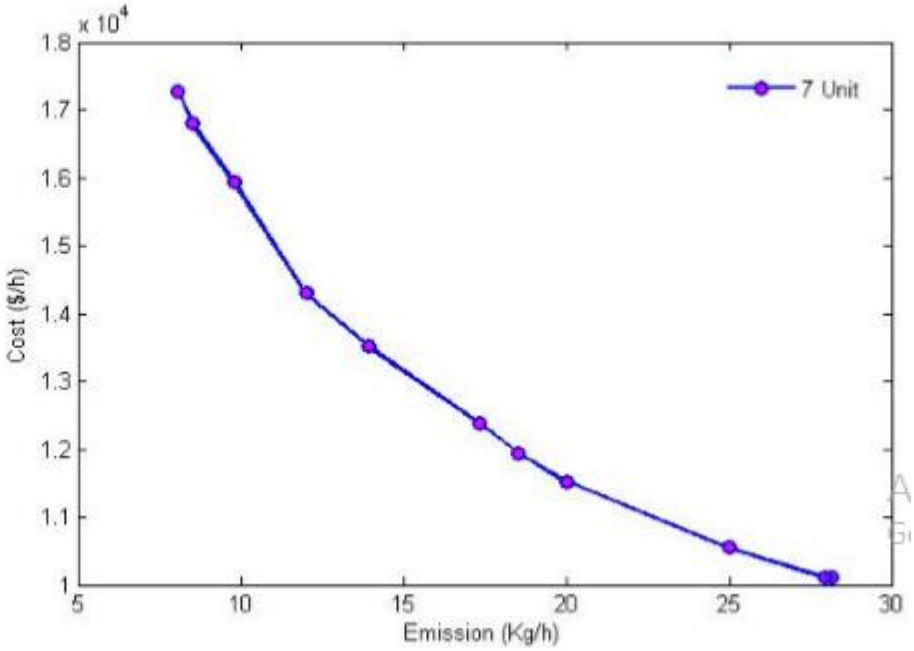

Figure 2 Pareto Optimal Front of 7-unit CHP system

CONCLUSION

This paper demonstrated the feasibility of employing GWA for efficient solving of combined heat and power economic emission dispatch with cogeneration sources. In this work we have investigated the potential of the algorithm in solving CHPD problems studying different cases. In the case of economic emission dispatch problem with second order cost functions, our proposal found better solutions compared to other methods. In a nutshell considering all the results for study with different characteristic, dimensions, demands and constraints it can be concluded GWA yields better feasible solutions mostly within the feasible operating region in terms of cost, than the previously reported results.Any advantage in this area will cause great improvement in engineering application, which by reducing generator fuel consumption, both increases the profit of Energy Company and serves the environment.

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