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Combined Heat and Power Dispatch using Time Varying Acceleration Coefficient Particle Swarm Optimization

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***Abstract*—Currently whole world is facing the problem of energy disaster. So to overcome this problem there is an urgent need to create awareness about optimal use of the energy, environmental and economic benefits and making a nation more energy-independent, for this one of the obvious thought is combined heat and power (CHP) or cogeneration. In this paper performance of TVAC_PSO is tested on two test cases of combined heat and power dispatch problem i) a recently introduced new test case taken from literature, ii) a new test case with valve point loading effect. The thought behind TVAC_PSO is to improve the seeking ability of the CPSO and to use a parameter automation strategy for appropriate balance between local and global search.**

***Index Terms*— Combined Heat and Power Economic Dispatch (CHPED), Classical PSO, Particle Swarm Optimization (PSO), Time Varying Acceleration Coefficients PSO, valve point loading effects.**

I. INTRODUCTION

Cogeneration or combined heat and power (CHP) is well-organized, hygienic, and consistent approach to generating power and thermal energy from a single fuel source. CHP or distributed generation can significantly increase the equipped efficiency and decrease energy costs and reduce the load on Electric Transmission Infrastructure through distributed generation. At the same time, CHP reduces the emission of harmful gases and offers an important role in environment benefits. The working process of CHP is exceedingly analogous to an automobile, where the engine offer the power to rotate the wheels and the consequent heat is used to keep the passengers warm in the cabin during the winter months. Combined heat and power system pick up nearly all of the heat it produces and install it on site. As the demand of electricity generation increases in the industrial level, a new act is introduced in 1980's, the Public Utility Regulatory Policies Act (PURPA). This act opened the field to improved efficiency, which gave a financial encouragement to approve CHP for industrial energy users. Those that have continued to generate their own power have appreciated fuel efficiencies as high as 90 percent. On a national level, CHP has the potential to compensate considerable quantities of emissions of CO2 and other like greenhouse gases. Cogeneration can have an overall energy efficiency that is more than double that of most electricity-only fossil fuel power plants by distributing the waste thermal energy from power generation that would otherwise be lost as waste heat.

In this paper considered a non-convex combined heat and power dispatch problem with the deliberation of highly non-linear feature like valve point loading effect. This feature prepared combined heat and power dispatch problem more complex then the economic load dispatch problem. Few works have been done by researchers on combined heat and power dispatch [1] [2].Most of the previous works has been done as the fuel cost functions are quadratic in nature. Various well known techniques such as Improved Genetic Algorithm [3], Hybrid of Genetic Algorithm with tabu search [4], Improved penalty function formulation for the Genetic Algorithm [5], Ant colony search algorithm [6], Multi objective method using a fuzzy decision index and GA [7], Harmony search algorithm [8], Evolutionary programming approach [9], An improved multi objective PSO algorithm is used in [10], For modeling inaccuracies and uncertainties, stochastic models are also proposed where both power and heat demands are treated as random variables and then the economic dispatch problem is solved using multiple objectives of cost, expected power and heat deviations [10-12], Self adaptive real-coded genetic algorithm [13], Mesh adaptive direct search algorithm[14], Bee colony optimization [15], for solving CHPD problems. An effective heuristic for combined heat-and-power production planning with power ramp constraints [16].In [17] Proposing a decision-making model using analytical hierarchy process and fuzzy expert system for prioritizing industries in installation of combined heat and power systems. In [18], the work has done on probabilistic production simulation including combined heat and power plants. Barely any work on non-convex CHPD problem have been done in the literature like, handling non-convex heat-power feasible region in combined heat and power economic dispatch [19] and N. Sinha, T. Bhattacharya [20] worked on non-convex combined heat and power dispatch problems using GA In this paper introduced the TVAC_PSO approach for solving the considered CHPED problems. Time varying acceleration coefficients (TVAC) [21] are employed for iteratively controlling the global and local search components in CPSO [22].

II. COMBINED HEAT AND POWER DISPATCH PROBLEM FORMULATION

Mathematically, the CHPED problem is formulated as: The minimization of cost function which is the objective of the CHPD problem,

$$C = \sum_{i=1}^{n_p} c_i(p_i) + \sum_{j=1}^{n_c} c_j(h_j p_j) + \sum_{k=1}^{n_h} c_k(h_k) \qquad (1)$$

Where
C = Total heat and power production cost,
c = Unit production cost,
p = Unit power generation,
h = Unit heat production,

The power and heat demand constraints of CHPD problem are:

$$\sum_{i=1}^{n_p} (p)_i + \sum_{j=1}^{n_c} (p_j) = P_D + P_L; \quad \textit{power balance constraint} \qquad (2)$$

$$\sum_{i=1}^{n_c} (h)_j + \sum_{j=1}^{n_h} (h_k) = H_D; \quad \textit{heat balance constraint} \qquad (3)$$

H_D = System heat demand,
P_D = System power demand,

For a given total real load P_D the system loss P_L in eq. (2) is a function of active power generation at each generating unit. The operational ranges of the heat and power unit are articulated as:

$$p_i^{min} \le p_i \le p_i^{max}, \; i=1,2,. \ldots\ldots n_p; \qquad (4)$$

Generating limit constraints

$$p_j^{\min(h_j)} \le p_j \le p_j^{\max(h_j)}, \qquad j = 1,2\ldots, n_c; \qquad (5)$$

FOR constraints

$$h_j^{\min(p_j)} \le h_j \le h_j^{\max(p_j)}, \qquad j = 1,2,\ldots n_c; \qquad (6)$$

FOR constraints

$$h_k^{min} \le h_k \le h_k^{max}, \qquad k = 1,2\ldots\ldots, n_h; \qquad (7)$$

Heat limit constraints

i, j and k are the indices of conventional power units, cogeneration units and heat only units mentioned above, np, nc, nh are the numbers of the kinds of units, mentioned above, pmin and pmax are the unit power capacity limits, hmin and hmax are the unit heat capacity limits. The feasible operation region of cogeneration units is explained through the inequalities of the operation ranges. The FOR is shown in fig. 1.

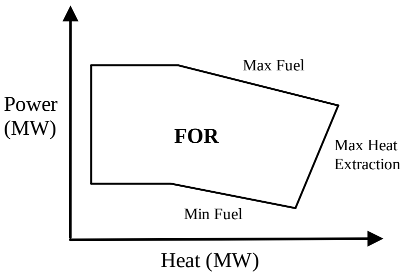

Fig 1 Cogeneration unit feasible operation region

III. ALGORITHM (TVAC_PSO) FOR CHPD PROBLEM

In this section, an improved PSO (TVAC_PSO) and CPSO algorithm are explained and TVAC_PSO is applied to solve the CHPD problems.

A. *CLASSICAL PARTICLE SWARM OPTIMIZATION*

Classical particle swarm optimization (PSO) is considered as realistic and powerful solution schemes to obtain the global or quasi-global optimums in power system optimization problems. Particle Swarm Optimization is a novel optimization method developed by Kennedy and Eberhart [22]. It is based on the performance of individuals of a swarm. The individual particles are drawn stochastically toward the position of present velocity of each individual, their own previous best performance, and the best previous performance of their neighbors. The position and velocity vectors of the ith particle of a d- dimensional search space can be represented as $(X_i = x_{i1}, x_{i2}, \ldots\ldots\ldots x_{id})$ and $(V_i = v_{i1}, v_{i2}, \ldots\ldots\ldots v_{id})$ respectively. On the basis of the value of the evaluation function, the best previous position of a particle is recorded and represented as $pbest_i = (p_{i1}, p_{i2}, \ldots\ldots p_{id})$. If the gth particle is the best among all particles in the group so far, it is represented as $pbest_g = gbest = (p_{g1}, p_{g2}, \ldots p_{gd})$. The particle tries to modify its position using the current velocity and the distance and the modified velocity and position of each particle for fitness evaluation in the next iteration are calculated using the following equations:

$$v_{id}^{k+1} = w \times v_{id}^{k} + c_1 \times rand_1 \times (pbest_{id} - x_{id}) + c_2 \times rand_2 \times \qquad (8)$$

$$x_{id}^{k+1} = x_{id} + v_{id}^{k+1} \qquad (9)$$

Here, w is the inertia weight parameter, C is constriction factor, c1 and c2 are cognitive and social coefficients, and rand1, rand 2 are random numbers between 0 and 1. The inertia weight controls the global and local exploration capabilities of the particle. The practice is to use larger inertia weight factor during initial exploration and gradual reduction of its value as the search proceeds in further iterations. The concept of time varying inertial weight was introduced in [15] as per which w is given by

$$w = (w_{max} - w_{min}) \times \frac{(iter_{max} - iter)}{iter_{max} + w_{min}} \qquad (10)$$

Where iter max is the maximum number of iterations. Constant c1 pulls the particles towards local best position whereas c2 pulls it towards the global best position. Usually these parameters are selected in the range of 0 to 4.

B. *TIME VARYING ACCELERATION COEFFICIENTS WITH PSO*

The PSO_TVAC [21] is population-based optimization method; in this method the policy is to encourage the individuals to roam through the entire search space, during the initial part of the search, without clustering around local optima. During the latter stages, however convergence towards the global optima should be encouraged, to find the optimum solution efficiently. In TVAC, this is achieved by changing the acceleration coefficients c1 and c2 with time in such a manner that the cognitive component is reduced while the social component is increased as the search proceeds. A large cognitive component and small social component at the beginning, allows particles to move around the search space, instead of moving towards the population best prematurely. During the latter stage in optimization, a small cognitive component and a large social component allow the particles to converge to the global optima. The acceleration coefficients are expressed as:

$$c_1 = \left(c_{1f} - c_{1i}\right)\frac{iter}{iter_{\max + c_{1i}}}$$

(11)

$$c_2 = \left(c_{2f} - c_{2i}\right)\frac{iter}{iter_{\max + c_{2i}}}$$

(12)

The velocity is calculated as:

$$v_{id}^{k+1} = C[w \times v_{id}^{k} + \left(\left(c_{if} - c_{1i}\right)\frac{iter}{iter_{\max}} + c_{1i}\right) \times rand_1 \times (pbest_{id} - x_{id})$$
$$+ \left(\left(c_{2f} - c_{2i}\right)\frac{iter}{iter_{\max}} + c_{2i}\right) \times rand_2 \times (gbest_{gd} - x_{id})] \qquad (13)$$

Where c1i, c1f, c2i and c2f are initial and final values of cognitive and social acceleration factors respectively. The evolutionary approaches are proposed by several researchers to solve power system optimization and other problems, because these approaches are based on natural phenomenon and hence are more vigorous and appropriate for real world problems. CPSO [22] and its advancement like TVAC_PSO techniques are most trendy, looking at the number of papers published during past few years. This section presents an i) in-depth review of TVAC_PSO approach ii) impact of tuning parameters. The TVAC_PSO results are compared with PSO variants using reliable such as convergence behavior, consistency and solution quality for solving the non-convex CHPED problem.

C. IMPLEMENTATION OF TVAC_PSO FOR CHPD SOLUTION

For implementation of the IPSO algorithm for solving CHPD problem with valve point loading effect the step by step procedure is:

Step 1) Parameter setup

The TVAC_PSO parameters such as population size, cognitive factor, social factor, constriction factor, Time Varying Acceleration Coefficients, Time Varying Inertia Weights, the boundary constraints of optimization variables and the stopping criterion or maximum number of iterations, are selected.

Step 2) Generation of initial population

This step ensures generation of a feasible population vector. The individuals in the population are randomly generated between the maximum and the minimum operating limits of the units respectively such that constraints given by eq.(4)-eq. (7) are satisfied.

Step 3) Constraint check of cogeneration units FOR region of the CHPED problem

This step ensures that all constraints of cogeneration units are satisfied or the heat and power demands must within the FOR region.

Step 4) Initialization of power only units of the population

The jth dimension (from j=1 to np) i.e. of power only units of the ith individual of the population is initialized as given below to satisfy the generation limit constraint given by (4). Here, r is a random number and r ∈ [0, 1].

$$P_{ij} = P_{ij\,min} + r\left(P_{ij\,max} - P_{ij\,min}\right)$$

(14)

Step 5) Initialization of heat only units of the population

The jth dimension (from j=np+1 to np + nh) i.e. of heat only units of the ith individual of the population is initialized as given below to satisfy the heat limit constraint given by (7).

$$\boldsymbol{h}_{ij} = \boldsymbol{h}_{ij\,min} + r\left(h_{ij\,max} - h_{ij\,min}\right)$$

(15)

Step 6) Initialization of power and heat of cogeneration units of the population

The jth dimension (from j=np+nh+1 to np+nh+nc) i.e. of the cogeneration units of the ith individual of the population is initialized as given below to satisfy the power and heat mutual dependency constraints as given by eq. (5) and eq. (6).

$$p_{ij} = p_{ij\,min}(\boldsymbol{h}) + r\left(p_{ij\,max}(h) - p_{ij\,min}(h)\right)$$

(16)

$$\boldsymbol{h}_{ij} = \boldsymbol{h}_{ij\,min}(p) + r\left(\boldsymbol{h}_{ij\,max}(p) - \boldsymbol{h}_{ij\,min}(p)\right)$$

(17)

Step 7) Fitness evaluation of each individual of the population

The fitness of each individual in the population is evaluated to judge its merit for CHPED problem using a function called evaluation function. The evaluation function is defined such that cost is minimized while power and heat balance constraints given by eq. (2) and eq. (3) respectively are satisfied and power losses are met. The popular penalty function method has proved very effective and simple in modeling complex equality constraints in multi-area dispatch [23]. The penalty function approach converts a constrained optimization problem into an unconstrained optimization problem. In this method, the penalty functions composed of squared or absolute violations are introduced in the fitness function such that an infeasible solution is awarded lesser fitness than the weakest feasible individual string. Since two infeasible individuals are not treated equally, the individual which is further away from the feasibility boundary is more heavily penalized compared to the one which is nearer to the boundary. The evaluation function used here is given by

$$\min [C + \alpha\left[\sum_{i=1}^{n_p} p_i] + \sum_{j=1}^{n_c} p_j - P_D\right]^2 + \beta\left[[\sum_{k=1}^{n_h} h_k - \sum_{j=1}^{n_c} h_j - H_D]^2\right. \quad (18)$$

Here, α and β are the power and heat penalty coefficients respectively. The second term imposes a penalty on the individual in terms of increased cost, if power balance constraint is not satisfied and the third term imposes a penalty, if heat balance constraint is not satisfied. The first term is calculated for each individual using eq. (1)

Step 8) Updating the best local position for each particle

The particles are updated the best local position to improve the fitness. Time varying acceleration coefficients are inserted to the updated velocity population to find the global best solution.

Step 9) Checking the updated population for bound violations:

The bounds on individuals specified by eq. (4) to eq. (7) may get violated after population updating process in step7-step8. Each dimension of an individual is checked for the binding constraints, and made to follow the minimum and maximum limits and FOR. Violated values are made to assume the nearest value on feasibility boundary.

Step 10) Stopping criterion: A stochastic optimization algorithm is stopped either based on the tolerance limit or maximum number of iterations. The tolerance limit can be set based on the standard deviation (S.D.) of population members. As the population moves towards convergence iteratively, the S.D. reduces, finally assuming a very small value. The number of iterations is adopted as the stopping criterion in this paper.

IV. CASE STUDIES AND RESULTS

The TVAC_PSO algorithm is tested on the proposed practical CHPED problems on two test cases having varied complexities. The obtained results are also compared with previously published results [9]. A program based on TVAC_PSO is developed in MATLAB (R2009a), version 7.8.0.347 and run on a 2.40 GHz, i5, with 4GB RAM CPU.

A. Description of test system

- *New test case [9]*

This case is a new test system proposed in [9]. In this system 1 boiler, 1 generator, 2 cogeneration units are present. The heat-power feasible operating region (FOR) of unit two and unit three is given in Fig. 2 and Fig. 3. The cost functions are:

$$c_1 = 254.8863 + 7.6997p_1 + 0.000172p_1^2 + 0.000115p_1^3 \quad (19)$$

$$c_2 = 2650 + 34.5p_2 + 0.1035p_2^2 + 2.203h_2 + 0.025h_2^2 + 0.051$$

$$c_3 = 1250 + 36p_3 + 0.0435p_3^2 + 0.6h_3 + 0.027h_3^2 + 0.011p_3h_3 \quad (21)$$

$$c_4 = 950.002 + 2.0109h_4 + 0.038h_4^2 \quad (22)$$

Minimize

$$C = \sum_{i=1}^{4} c_i \qquad i = 1, \ldots\ldots 4 \quad (23)$$

Subject to

$$35 \leq p_1 \leq 135MW \quad (24)$$

$$0 \leq h_4 \leq 60MW \quad (25)$$

$$P_D = p_1 + p_2 + p_3 \quad (26)$$

$$H_D = h_2 + h_3 + h_4 \quad (27)$$

Three load cases are considered here.

i) PD=205 MW, HD=125MWth
ii) PD=250 MW, HD=175MWth
iii) PD=250MW, HD=240MWth

- *New test case with valve point loading effects*

This system consist new test case [9] with valve point loading effects which is introduced by authors; consists of four generating units, two cogeneration units, a conventional power only units, one heat only unit. This system modified to include valve point loading effects. The heat-power feasible operating region (FOR) of unit two and unit three is given in Fig. 2 and Fig. 3.

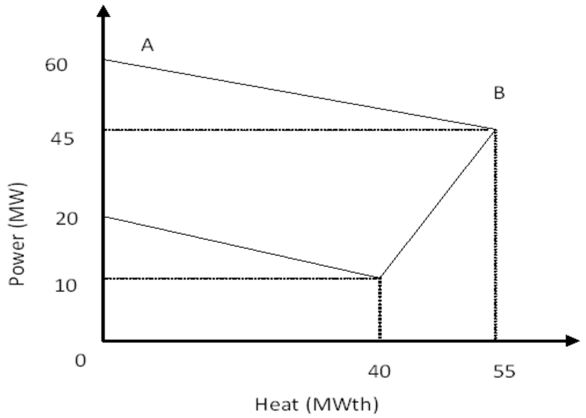

Fig. 2. FOR of cogeneration unit 2 for test case-I and case II

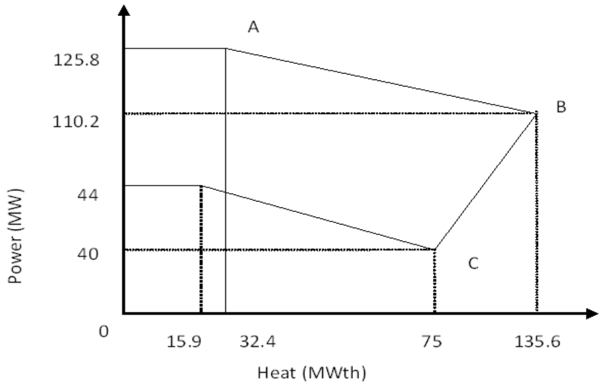

Fig 3. FOR of cogeneration unit 3 for test case-I and case II

I. Valve point loading effects:

The valve-point effects initiate ripples in the heat-rate curves and formulate the objective function discontinuous, non-convex and with multiple minima. For accurate modeling of valve point loading effects, a rectified sinusoidal function [24] is added in the cost function in this Paper. The fuel input-power output cost function of ith unit is given as

$$F_i(P_i) = a_iP_i^2 + b_iP_i + c_i + |e_i \times \sin(f_i \times (P_{\min} - P_i))| \quad (28)$$

II. The cost functions are:

$$c_1 = 254.8863 + 7.6997p_1 + 0.00172p_1^2 + 0.000115p_1^3 + \mathrm{abs}(100\sin(0.053(35 - p_1))) \quad (29)$$

$$c_2 = 2650 + 34.5p_2 + 0.1035p_2^2 + 2.203h_2 + 0.025h_2^2 + 0.051p_2h_2 \quad (30)$$

$$c_3 = 1250 + 36p_3 + 0.0435p_3^2 + 0.6h_3 + 0.027h_3^2 + 0.011p_3h_3 \quad (31)$$

$$c_4 = 950.002 + 2.0109h_4 + 0.038h_4^2 \quad (32)$$

Different load demands and load cases are same as new test case [9] mentioned above.

B. Parameter Setup

For both the considered test cases, parameter setup is same. Different population sizes were tested. Stopping criterion was 10000 iterations for both algorithms. In PSO both the coefficients c1 and c2 are taken as 2.0 and in PSO_TVAC coefficient c1 is iteratively varied from 2.5-0.2 and c2 from 0.2 to 2.5[21] in a linear manner. Penalty coefficients and are both taken as 10^5. A lower value was producing violations of heat and power, while a larger value gives convergence to a feasible result but higher cost. Different trials with different random initial populations were carried out to establish the consistency of the results.

C. Results for New test case

This case study introduced by K.P. Wong and C. Algie [9]. Table 1, 2, 3 presents the best solution of this problem for different demand cases found using TVAC_PSO algorithm and obtained the same as the best known solution. Here, only the optimal solutions are considered.

For all the demand cases there is writing mistake in the results presented in table of new test case [9]. The ⇄ Represents the interchanging the values of the cogeneration units like, value of p_2 is interchanged with h_2, and p_3 is interchanged by h_3. All cases were run for five trials each and each trial was allowed a maximum from 10^2- 10^4 iterations. Statistical analysis has also done for new test case with varying demand levels to test the consistency of the TVAC_PSO for CHPD problems.

Table I. Solution for demand case (PD=205, HD=125)

Method	P_1	P_2	h_2	p_3	h_3	h_4	Cost ($)
TVAC_ PSO	**135.0**	**24.0**	**24.5**	**46.0**	**65.5**	**35.0**	**9498.00**
NEW CASE [9]	135.0	24.5	24.0	65.5	46.0	35.0	9498.48

Table II. Solution for demand case (PD=250, HD=175)

Method	P_1	P_2	h_2	p_3	h_3	h_4	Cost ($)
TVAC_ PSO	**135.0**	**35.5**	**39.4**	**79.5**	**83.3**	**52.3**	**11666.98**
NEW CASE [9]	135.0	39.4	35.5	83.3	79.5	52.3	11666.98

Table III. Solution for demand case (PD=250, HD=240)

Method	P_1	P_2	h_2	p_3	h_3	h_4	Cost ($)
TVAC PSO	**119.0**	**20.2**	**44.3**	**110.2**	**135.6**	**60**	**12676.4**
NEW CASE [9]	119.7	44.4	20.1	135.6	110.2	60	12671.4

Table IV.Statistical performance for new test case for varying demand levels

Load Demand		Minimum Cost	Mean Cost	Maximum Cost	S.D.
PD	HD				
205	125	9498.7	9516.7	9539.3	12.6978
250	175	11666.10	11688.0	11729.0	15.4932
250	240	12676.41	13536.0	14488.0	659.4000

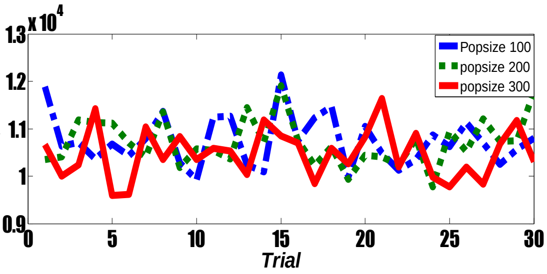

Fig 4. Consistency analysis of new test case at (PD=205, HD=125)

This figure shows that applied algorithm is quite consistent. The best result is obtained at population 300.

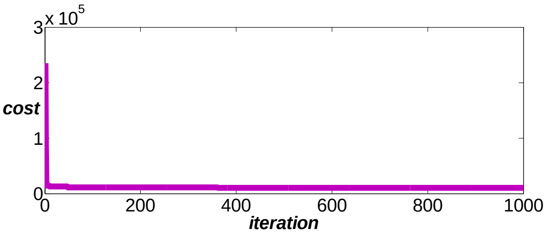

Fig 5. Convergence characteristic of new test case at (PD=205, HD=125)

This figure shows the convergence characteristic using proposed algorithm for 1000 iteration which represents the seeking ability of the algorithm.

D. Results for new test case with valve point loading

In this section, best results for the different demand levels using the TVAC_PSO algorithm. All cases were run for thirty trials each and each trial was allowed a maximum of

10^4 iterations.

Table V.Best results for new test case with valve point loading effects

Load Demand		Minimum Cost	Mean Cost	Maximum Cost	S.D.
PD	HD				
205	125	9598.39	10473.0	11634.0	435.162
250	175	11774.89	12078.0	12673.0	191.173
250	240	12784.90	13108.0	13466.0	253.650

Table VI.Statistical performance for new test case with valve point loading effects

Demand levels	P_1	P_2	h_2	p_3	h_3	h_4	Cost ($)
PD=205, HD=125	134.9	20.41	34.70	49.60	53.57	36.72	9598.39
PD=250, HD=175	135.0	37.27	50.15	77.72	64.86	59.98	11774.8
PD=250, HD=240	119.5	20.14	44.40	110.3	135.6	59.9	12784.9

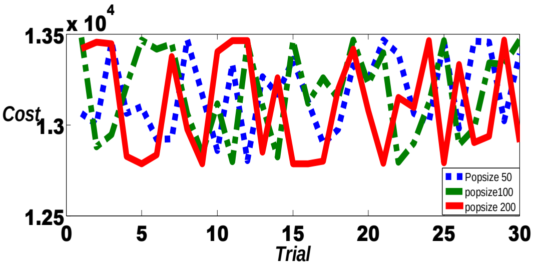

Fig 6. Consistency analysis of VPL new test case at (PD=250, HD=240)

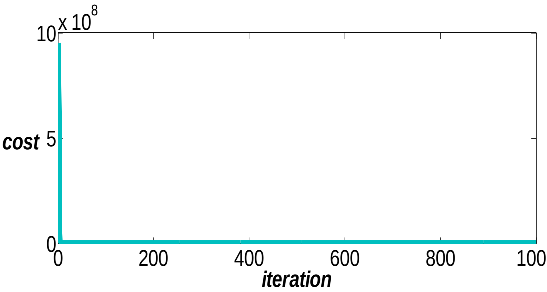

Fig 7.Convergence characteristic of VPL new test case at (PD=250, HD=240)

This figure shows the consistency analysis of the VPL CHPD problem at power demand 250 and heat demand 240, for the different population sizes. The consistency analysis using the proposed algorithm obtained best result at population 200. This figure represents that the proposed algorithm creates good convergence behavior.

V. CONCLUSION

In this paper TVAC-PSO algorithm has been employed to solve two test cases of combined heat and power dispatch problem and results are compared with previous results available in literature. The CHPD problem is difficult to solve due to the heat and power mutual dependence constraints and FOR of cogeneration units. The results obtained by proposed method demonstrate that the proposed algorithm is quite consistent and produces solutions of high quality. The best results for new test case with valve point loading effects also obtained and minimum cost is achieved with full satisfaction of all constraints. Simulations are carried out, under varying heat and power demand levels. The main findings can be summarized as:

- TVAC_PSO algorithm was found to give global convergence for test cases with full satisfaction of FOR constraints of cogeneration units and heat and power balance.
- This shows the better search capability of the method to explore the complex search domain very effectively.
- The TVAC_PSO algorithm is very stable and consistent. It has been shown to perform well for non-convex CHP dispatch case also.

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