Combined Heat and Power Economic Dispatch by using Modified Particle Swarm Optimization

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Submitted by

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DECLARATION

I hereby certify that the work which is presented in a dissertation entitled, "**Combined Heat and Power Economic Dispatch by using Modified PSO**", in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of Dr. Nitin Narang. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in the text and references.

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NOMENCLATURE

F_T	Total fuel cost of thermal units ($)
P_i	Power generation by i^{th} thermal power unit
P_j	Power generation by j^{th} cogeneration unit
P_D	Total power demand
H_D	Total heat demand
N_P	Number of thermal power units
N_b	Number of cogeneration units
N_h	Number of heat-only units
i	Index of thermal power units
j	Index of cogeneration units
k	Index of heat-only units
C_i	Cost of unit production of conventional generators
C_j	Cost of unit production of cogeneration units
C_k	Cost of the unit production cost of heat-only units
v_{ij}^r	Velocity of i^{th} particle of j^{th} member at r^{th} iteration
P_{ij}^r	Current position of member of i^{th} of j^{th} member at r^{th} iteration
R_1, R_2	Random variables lies between [0, 1]
C_1, C_2	Acceleration coefficients
G_j^{best}	Global best position out of all the best position
w	Inertia weight factor
g	Gaussian distribution functions

σ^2	Standard deviation which is taken as '1'
r	Current number of iteration
r^{max}	Maximum number of iterations
C_{1f}, C_{1i}, C_{2f}, C_{2i}	Initial and final acceleration parameter

ABBREVATIONS

CHP	Combined Heat and Power.
CHPED	Combined Heat and Power Economic Dispatch.
EP	Evolutionary Programming
PSO	Particle Swarm Optimization
TVAC	Time Variant Acceleration Coefficient
GA	Genetic Algorithm
DE	Differential Evolution
MPSO	Modified Particle Swarm Optimization.
SCA	Society Civilization Algorithm
GSO	Group Search Optimization
CSO	Civilized Swarm Optimization.
SQP	Sequential Quadratic Programming
HS	Harmony Search
ACO	Ant Colony Optimization

ABSTRACT

The main objective of Combined Heat and Power (CHP) generation scheduling is the optimal generation with the combination of heat and power units for the minimization of generation cost, along with the satisfaction of heat and power demand constraints and load demand. The efficiency of thermal only unit is relatively less, hence to increase the efficiency of overall system cogeneration units is used. For cogeneration units heat is a primary output and can further be utilized to produce secondary generation without the involvement of extra heat. It can also be utilized as process heat in manufacturing industries. In CHP generation scheduling, heat and power being the non-separable units, constraint handling becomes a difficult task. Along with this, the complexity of the problem increases when multiple CHP systems are taken into consideration.

In the underlying work, Modified Particle Swarm Optimization (MPSO) has been used to solve CHPED problem. Although PSO is a well recognized optimization technique, still for multi modal problems, it can strike to a local optimal solution. In the modified PSO, conventional PSO is replaced by Gaussian PSO and Time Variant Acceleration Coefficient (TVAC-PSO). To handle constraints of the problem, exterior penalty factor is used. The modified PSO is tested on well recognized test problem and found satisfactory.

CHAPTER-1

INTRODUCTION

1.1 Introduction

The efficiency of conventional thermal power plant is very low (in the range of 40-60%). This is because waste heat is not utilized by them. Combined Heat and Power (CHP) on the other hand, effectively utilizes the waste heat of thermal power plant. So, it is preferable to use CHP to achieve the maximum possible efficiency in the generation process. To improve the overall efficiency, it has been recommended by various researchers, the use of heat can be helpful to produce power. This means that to produce the same amount of useful energy less amount of fuel is required [1].

The most economic method that is used for generating power from the single fuel source is combined heat and power (CHP). In order to achieve the maximum possible efficiency, it is to be preferable to use CHP for producing electricity [2]. CHP is more efficient and clean process, in combined system fuel requirement is comparatively very less as compared to the produced energy than with separate heat and thermal units. Higher efficiency interprets that:

- Operating cost is less.
- It also reduced emissions of all pollutants.
- Increased reliability and power quality.

Most of the industries are now using cogeneration systems. The industries which need both power and heat can supply their own demand with CHP systems. They can also be used as distributed electrical energy sources and can be developed in grown-up areas [3].

The objective is finding out the optimal schedule of generators such that the cost of power generation can be minimized [10]. Along with this, both heat and power demand constraints and other system equality and inequality constraints are met. Further, the CHP units should operate in a feasible operating region [4].

1.2 Literature Review

Researchers have explored some of the conventional optimization techniques to solve CHP dispatch problems. Cho *et al*. [5] have formed an energy dispatch algorithm to solve the CHP problem. The selection of optimal operational mode has resulted in optimal energy cost. Liu *et al*. [6] solve the CHPED problem of combined cycle gas turbine generating units by using mixed integer programming and lagrangian relaxation (LR) method. Aramburo *et al*. [7] applied a unit commitment operation to solve the CHP problem in a microgrid. This is done by satisfying heat demand and power demand constraints. Rooijers and Van Amerongen [8] employed a model which includes two levels. The lambda's sensitivity coefficients are updated on the upper level and in the lower level the economic dispatch problem is solved. Hawkes and Leach [9] discussed a linear programming method to solve CHP problem, which is based on a unit commitment for a microgrid with an objective, is to produce output so that cost is to be minimized.

The Conventional techniques have some of the disadvantages as [7]:

- Able to find only a single optimized solution.
- Poor convergence characteristics.
- Qualitative constraints are hard to handle.

To overcome the demerits of classical methods, various researchers have explored global search techniques like genetic algorithm (GA) [10-13], particle swarm optimization (PSO) [14-21], modified particle swarm optimization (MPSO) [22-37], differential evolution (DE) [38-48], society civilization algorithm (SCA) [49], group search optimization (GSO) [50-51], etc. Chang and Fu [10] employed a test system consisting of seven generators to implement fuzzy index and GA on it for the solution of CHP problem. For improving the efficiency of a system in CHPED problem, Song and Xuan [11] proposed an improved penalty function method of GA to solve the economic dispatch problem. Guo *et al*. [12] have solved CHP problem by decomposing the problem into power and heat dispatch sub-problems. To solve the nonlinear optimization problem of CHPED, an algorithm which is based on sequential quadratic programming is suggested by Chapa and Galaz [13].

Among the various optimization techniques, PSO is one of the most effective global search techniques. Particle swarm optimization has a higher rate of convergence ,thus, for better performance it gets trapped into local minima and the problem does not converge optimally and searching process reaches the local search region and not able to give the best solution [14]. Tyagi and Pandit [15] recommended the solution of CHPED problem by using PSO, to determine the heat and power production in such a way that production cost is minimum and overall efficiency becomes high. Jun *et al*. [16] investigated the searching capability of a particle using quantum-behaved PSO algorithm and its novel based control method to solve the problem of CHPED. Shayanfar *et al*. [17] presented a PSO with improved inertia weight factor for solving CHPED problem. Ramesh [18] presented a new variant, selective PSO technique for CHP, which results in an improved speed of convergence and is function formulation for GA, to solve CHPED problem. Wang and Singh [19] suggested the stochastic model for CHPED problem, and then by considering multiple objectives improved PSO is simultaneously deal with economic CHP. Umayal and Kamaraj [20] used PSO for multi-objective ED problem along with emission control. Objectives include the cost of generation, CO_2, NO_x, SO_x forming multi-objective ED problem. Weight to each objective is given according to its importance in power system and final objective function is formed. Bo *et al.* [21] implemented multi-objective PSO for ED problem. Considered constraints are active and reactive power balance, line constraints, generator limits with three objectives of minimizing fuel cost, power loss, and emissions. Different Pareto optimal solutions are obtained which are further solved with Fuzzy based linear membership function. A best compromising solution is finally taken off from the tradeoff curve.

Researchers have explored some of the variants of PSO to solve CHP dispatch problems. Park *et al.*[22] implemented modified PSO for solving CHPED problem. Here, equality constraints are handled by a heuristic technique whereas, the inequality constraints are handled through position adjustment strategy for ED problem. The dynamic space reduction is observed in this technique between Global best and max. and min. generator output.Lee [23] used a Multi-Pass Iteration PSO for minimizing the cost of generation and startup cost including the constraints like power balance equality constraints, ramp rate limit , and limits for a generation. This method improves computational efficiency when compared to conventional PSO. It has the ability of randomly searching the space and time staging which refines the interval between two time stages. New index of best iteration further helps in controlling the movement of particles. Ivatloo *et al.* [24] suggested time varying acceleration coefficients (TVAC) method, which is modified version of PSO to solve ELD problem. ELD problem is considered to be non-linear and non-convex in nature. Subhani *et al.* [25] proposed PSO based on automation strategy including TVAC (Time-Varying Acceleration Coefficients). TVAC can handle premature convergence efficiently for the solution of ELD problem. Hadji *et al.* [26] suggested a multi-objective TVAC-PSO to solve the economic dispatch problem. In this methodology, a new variant is introduced to modify the solution of ED problem. Acceleration coefficients are modified in order to improve the performance of conventional PSO and to balance its search capability. The main objective of this approach is to minimize the total fuel cost with the consideration of total power losses. Muneender *et al.* [27] proposed PSO with TVAC for managing congestion in lines. Real power generation is rescheduled optimally by forming a constrained non-linear optimization problem and applying PSO-TVAC on it. This helps in relieving congestion in heavily loaded lines. It is seen that PSO-TVAC gave better results than conventional PSO. Das and Coelho *et al.* [28] proposed pricing of reactive power with the help of TVAC-PSO. Reactive power zonal market and bidding structure decide the reactive power dispatch. For consumers, reactive consumption, voltage control, and the cost of unused capacity decide the charge. Tracing method and sensitivity method are employed for cost allocation. It is seen that tracing method is far superior to the sensitivity method. Achayuthakan and Ongsakul [29] Suggested Modification of conventional PSO for the solution of ELD problem. It is seen that this modified version of PSO has proved to be better in the case of reliability and accuracy for tracing a solution which is constantly varying and having a suitable fitness. Its convergence is also very quick which determines its effectiveness as compared to its counterpart. Saber *et al.* [30] Used improved PSO including constraints like ramp rate limits and prohibited operation zones with the inclusion of loss criteria. This improved PSO guarantees the feasibility of solution thus giving better speed, accuracy, and convergence.

Xin et *al.* [31] Used Gaussian PSO for solving ELD problem which includes non-linear generator features. This method performs better than meta-heuristic optimization techniques. PhanTu et *al.* [32] proposed a novel weight improved PSO for OPF and ELD problems. Santhi and Subramanian [33] suggested adaptive binary PSO based unit commitment problem. Singh and Kumar [34] applied ELD with environmental emission using moderate-random PSO. Melo and Watada [35] trained a neural network with the help of Gaussian PSO with a fuzzy system based on structural learning. The main advantage of Gaussian PSO is that the problem of parameter dependence is eliminated. In Gaussian distribution, randomly defined numbers replace the acceleration constant. Pant *et al.* [36] proposed Gaussian distribution PSO algorithm to solve the ELD problem. Das Gupta *et al.* [37] proposed different basic structures of modified PSO i.e. PSO with inertia weight factor, PSO with constriction factor and PSO with a combination of both inertia weight factor and constriction approach method to solve the ELD problem.

Basu [38] presented artificial immune system approach for the solution of CHPED problem. Song and Xuan [39] to solve the economic dispatch problem of CHP, improved ant colony search algorithm are investigated. Larsen *et al*. [40] discovered probabilistic production simulation technique for solving CHPED problem. Sabramooz *et al*. [41] carried out a comparative study of meta-heuristic and mathematical optimization approaches for solving the CHPED problem. This study evaluated the optimization techniques and discussed its weakness and strength in solving a large-scale optimization problem. Basu [42] investigated DE method for solving CHPED. There are very fewer parameters to be set by DE. Montes et al. [43] proposed a DE based algorithm to solve constrained optimization problem in CHP formulation. Sinha *et al*. [44] analyzed the DE performance for the solution of CHPED problem. Vahedi *et al*. [45] discovered a DE-based optimization technique to solve the CHP problem. Najafi *et al*. [46] solve CHPED problem by using improved DE approach. Michalewicz and Schoenauer [47] compared and surveyed different constraint-handling techniques, which are used in evolutionary algorithms for solving CHPED problem. The comparison showed that for handling constraints, the penalty function method is one of the best. Kukkonen and Lampinen [48] proposed DE method for solving CHP problem by using vector differences stochastic function optimizer.

Ray *et al.* [49] proposed society civilization algorithm (SCA) by using Intra and inter-society interactions to solve the problem of constrained optimization in CHP units. He *et al*. [50] investigated group search optimization (GSO) for CHP problem. Shen *et al*. [51] checked the performance of group search optimization (GSO) for solving CHP problems. This has resulted in GSO as an alternative approach for constrained optimization. For solving the CHP problem in a limited time period modified GSO is to be used. Pipattanasomporn *et al*. [52] developed an optimal solution of distributed generating model using the mixed integer linear program to solve the CHP problem without any emission of the constraints.

Above discussed global search techniques have some merits and demerits. The main advantage is that its implementation is simple and it can give multiple optimized solutions in a single simulation. They can result in much more convergence. To overcome the demerits of one technique over the other, integrated techniques came into the picture. For better results and higher efficiency, it is also possible to integrate two different algorithms in a single unit.

Victorie and Jeyakumar [53] used hybrid PSO along with Sequential Quadratic Programming (SQP) for the solution of ELD problem. The constraints considered in this problem are load bus voltage, line constraint, spinning reserve constraint, ramp rate limit constraint, real power balance constraint, and generator limit constraint. PSO works as the main optimizer in this problem whereas, SQP works as a local optimizer. Local optimizer here gives a fine tuning to the region of the solution. Initially, PSO gives the global best solution which is further fine tuned by SQP. SQP accepts the solution of PSO as its initial searching point. This whole procedure helps in the exploration of global optimum at an earlier stage.

Jayabarthi [54] *et al.* used hybrid DE (HDE) algorithm and PSO for solving Economic Dispatch problem. Fuel cost is minimized subjected to active and reactive power balance and inequality constraints. It is observed that the result is similar in both cases but PSO has a faster convergence than HDE.

Ting [55] investigated a hybrid optimization technique which incorporates the features of both GA and harmony search (HS) for solving the CHP problem. Su and Chiang [56] used an integrated approach for CHPED problem. This approach includes improved GA with multiplier updating. The advantage of this approach is that it automatically adjusts the penalty function to an appropriate value and requires small population size. Selvakumar *et al.* [57] solved the CHPED problem by integrating two different global techniques such as civilized swarm optimization (CSO) and society civilization algorithm (SCA). With this approach, it is to be observed that overall efficiency for a set of set of multi-minima economic load dispatch improved and better results was obtained. Sudhakaran and Slochanal [58] discussed hybridization of GA with tabu search (GT) for solving CHP problem. Jalalzadeh [59] has analyzed the operation of CHP and CCHP (combined cooling heat and power) systems. Attaviriyanupap *et al.* [60] proposed a hybridization of EP and SQP technique to solve CHPED problem with nonsmooth fuel cost function. Elaiw *et al.* [61] proposed an integrated approach using DE and SQP for CHPED problem. This has the added advantage of reduced computational time which makes it more accurate and beneficial.

1.3 Objective of the Work

In this dissertation work, CHP problem is solved by using modified PSO. In modified PSO, TVAC-PSO and Gaussian PSO have been applied. The modified PSO improves the exploitation capability of search algorithm. Euclidean distance approach is used to handle inequality constraints for cogeneration units.

1.4 Organization of Dissertation

The proposed research work entitled as “Combined Heat and Power Economic Dispatch by using Modified Particle Swarm Optimization” has been organized in six chapters. Chapter one gives a brief introduction, literature survey, and objective of the dissertation work. Chapter two provides a detail introduction to CHP Economic Dispatch problem and its classification. It also introduces the formulation of CHPED problem. Chapter three highlights the basic idea of PSO and its applications in power systems. Further, this chapter also introduces modified PSO. To versions of modified PSO has been discussed i.e. TVAC-PSO and Gaussian PSO. Chapter four presents the algorithm to solve CHPED problem using modified PSO. Chapter five discusses the results obtained on applied test system. Chapter six includes the conclusion and future scope related to the work.

CHAPTER-2

COMBINED HEAT AND POWER ECONOMIC DISPATCH

2.1 Introduction

One of the well known and most established technologies in the power system is combined heat and power generation. The main advantages of CHP are its higher efficiency and less emission of greenhouse gasses [25]. CHP differs from the conventional plant in context to the type of power generated. In the case of a conventional plant, the output is only in electrical form whereas CHP generates both thermal and electrical energy which increases its efficiency. Due to the efficient use of waste heat, the efficiency of CHP unit is increased to 70-80% from 35-45% of the conventional case [17].The system becomes complex due to the non-separable nature of heat and power units in CHP operation. The problem formed is two-dimensional in nature, which complicates the economic dispatch problem.

2.2 Classification of CHP Systems:

2.2.1 Topping cycle CHP systems: It is the most widely used cogeneration method. In this cycle, primary production is electrical energy and secondary production is thermal energy. The thermal energy is the by-product of primary production. It is used as process heat and other requirements in production industries [14].

2.2.2 Bottoming cycle CHP systems: In this cycle, primary production is high-temperature thermal energy and secondary production is electrical energy from rejected heat of primary process. It is most beneficial for manufacturing industries which need high-temperature heat as input to furnaces and kilns. The rejected heat is also high in temperature and can further be used to produce electrical energy. Gas, cement, and petrochemical industries are common examples of bottoming-cycle CHP plants [14].

Topping cycle CHP plant is shown in figure (2.1) [19]. The basic components of topping cycle include heat recovery system generator (HRSG), gas turbine systems and steam generator systems. The heat from the gas turbine system is utilized by HRSG system. This exhausted heat is used to produce steam which is further used to operate the steam generator [16]. To increase the plant efficiency instead of HRSG system, duct firing heaters can be used. Due to this operation become more flexible. Thus, optimization of fuel cost is the main objective of this system, which can be achieved by minimizing the rate of change of power and heat units [17].

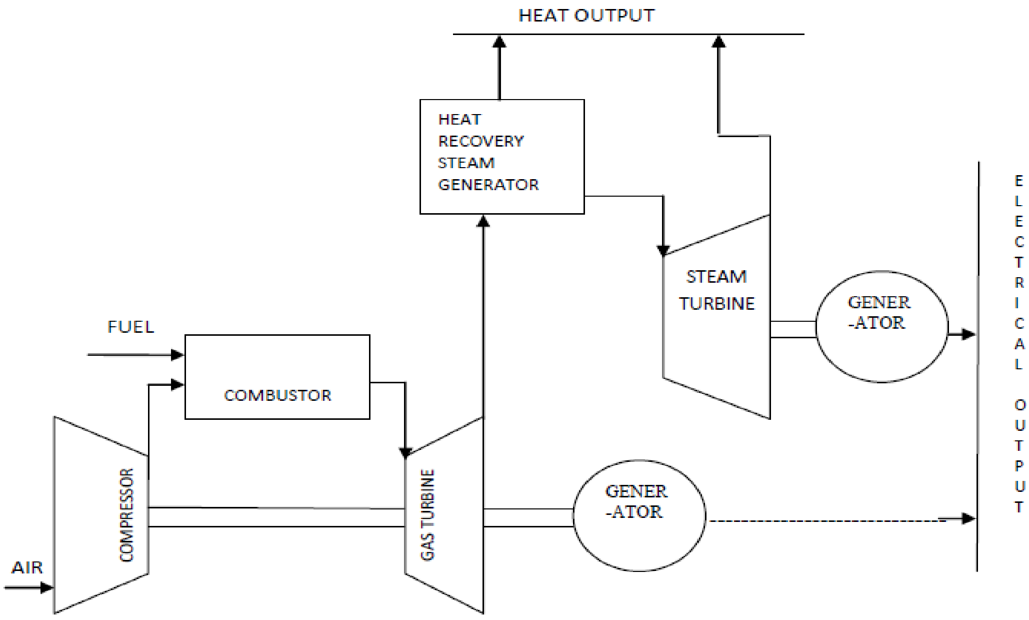

Fig. 2.1 Typical combined cycle CHP plant [19]

2.3 Problem Formulation of CHPED

For meeting the power demand, the loads on various generators are determined by static dispatch problem. By this optimal scheduling is done for least cost operation [22]. The main difference between CHPED and conventional ED is that the later deals with loads of conventional thermal generators only whereas, CHPED is much more complicated. CHPED involves power demands and process heat demands to be satisfied. In this power is generated by conventional thermal and cogeneration units whereas heat is being generated by heat-only and cogeneration units. Cogeneration units have heat and power loads which are non-separable in nature. This non-separable nature further increases the complexity of CHPED problem [25].

The system in consideration consists of thermal generators, heat-only units, and cogeneration units. CHP unit has a heat-power feasible operation region (FOR) which is depicted in figure (2.2) the enclosed area under the curve ABCDEF gives FOR [59]. When heat capacity increases, power generation starts decreasing along the curve BC and heat capacity decreases along CD respectively. The maximum and minimum limits of heat and power units describe their boundary conditions or operating limits. For the generation of heat, heat-only units are considered and similarly power-only units generate power [28]. The problem has the objective of minimizing the fuel cost and finding out the optimal generations and it can be mathematically stated as [31]:

Minimize

$$f_{\cos t} = \sum_{i=1}^{N_p} C_i(P_i) + \sum_{j=1}^{N_b} C_j(P_j, H_j) + \sum_{k=1}^{N_k} C_k(H_k) \tag{2.1}$$

2.3.1 Equality constraints

For balancing the power equation, the equality constraints must be satisfied as given in Eq. (2.2). Total demand, when added to total losses, make up the total power generated [28]. Equality constraint is stated as:

$$\sum_{i=1}^{N_P} (P_i) + \sum_{j=1}^{N_b} (P_j) = P_D + P_L \tag{2.2}$$

where, P_i is the power generation by i^{th} thermal power unit, P_j is Power generation by j^{th} cogeneration unit, P_D is total power demand, P_L is total line transmission losses, N_P is number of thermal power units, N_b is the number of cogeneration units, i defines the index of thermal power units, j defines the index of cogeneration units and k defines the index of heat-only units.

$$\sum_{j=1}^{N_b} (H_j) + \sum_{k=1}^{N_k} (H_k) = H_D \tag{2.3}$$

where, H_k is the heat generation by j^{th} cogeneration unit, H_k is the heat generation by k^{th} heat-only unit, N_b is the number of cogeneration units, N_h is the number of heat-only units and H_D is total heat demand of the system.

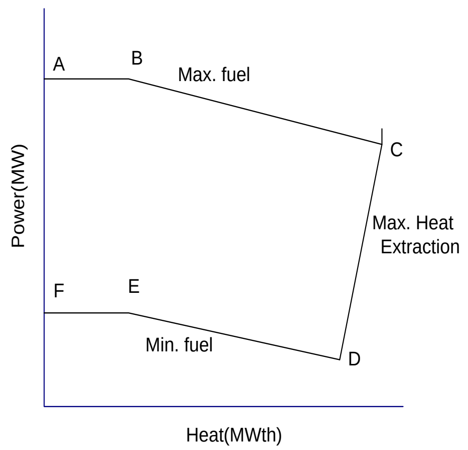

Figure 2.2 Heat-power feasible operating region for cogeneration unit [38].

2.3.2 Inequality constraints

The inequality constraints are represented by the upper and lower limits of all the units which totally depend on upon their operational curves [28]. The output values of all the units must lie between their maximum and minimum limits. Working limits for heat and power generation units are:

$$P_i^{min} \le P_i \le P_i^{max} \qquad i = 1, 2..........N_p \qquad (2.4)$$

$$P_j^{min}(H_j) \le P_j \le P_j^{max}(P_j) \qquad j = 1, 2..........N_b \qquad (2.5)$$

$$H_j^{min}(P_j) \le H_j \le H_j^{max}(P_j) \qquad j = 1, 2..........N_b \qquad (2.6)$$

$$H_k^{min} \le H_k \le H_k^{max} \qquad k = 1, 2..........N_k \qquad (2.7)$$

with

$$C_i(P_i) = a_i P_i^2 + b_i P_i + c_i \qquad i = 1 \qquad N_p \qquad (2.8)$$

$$C_j(P_j, H_j) = a_j P_j^2 + b_j P_j + c_j + d_j H_j^2 + e_j H_j + f_j P_j H_j \qquad j = 1, 2 ....N_b \qquad (2.9)$$

$$C_k(P_k) = a_k P_k^2 + b_k P_k + c_k \qquad k = 1, 2..........N_k \qquad (2.10)$$

where, P is the unit power generation, H is the unit heat production, C_i is the cost of unit production of conventional generators, C_j is the cost of unit production of cogeneration units, C_k is the cost of the unit production cost of heat-only units.

The limits on decision variables are defined in Eq. (2.4) to (2.7). The output of cogeneration units is non-separable in nature. H_D and P_D represent the system heat and power demands respectively. P_{min} and P_{max} are the unit power capacity limits. H_{min} and H_{max} are the unit heat capacity limits [16].

2.3.3 The active power transmission line losses

Line losses are considered as a very important factor and can be found out by using the formula given as [38]:

$$P_L = \sum_{i=1}^{N_b} \sum_{i=1}^{N_b} P_i B_{ij} P_j \qquad (2.11)$$

Where, P_L represent active power transmission losses, B_{ij} is the loss factor for a branch connected between 'i' and 'j' node [60].

CHAPTER-3

MODIFIED PARTICLE SWARM OPTIMIZATION

3.1 Introduction

The non-linear nature and inclusion of equality and inequality constraints make most of the optimization problems complex. Many conventional and non-conventional techniques are successfully employed to solve these complicated optimization problems. Some of the non-conventional techniques involved are a Genetic algorithm (GA), PSO, DE etc. Out of these, PSO is one of the most powerful techniques for the solution of non-linear and non-convex optimization problems [11]. A swarm is a group of particles which moves in a predefined search space. By their personal best experience, they acquire local best position and by the neighborhood experience, they acquire global best. During this search, every particle keeps a track of the position in the pre-defined search area [19].

PSO is search based on random population initialization which traces its solution on the basis of bird's movement for food. This search is parallel in operation and it explores every solution. The information is gathered by these particles through their own and neighbor's experience. The velocity of the particle is updated by the inertia weight which determines the momentum of a particle [21]. The direction of search is totally dependent on the value of inertia weight. If the inertia weight factor is greater than zero, the system shows divergent behavior due to increased system velocity. At this stage, particles are not able to acquire their best positions. Similarly, if inertia weight factor is less than zero, particles decelerate resulting in slower convergence. So, those inertia weight values are chosen which converges to the best solution [23].

3.2 Particle Swarm Optimization

Particle Swarm Optimization was introduced by Kennedy and Eberhart in the year 1995. It is a strategy by which birds and fishes search for food. This strategy being self-adaptive in nature is implemented successfully on different optimizing problems [22]. Very complicated problems related to power system can be effectively solved by the help of PSO. PSO determines the social behavior of birds and fishes. Particles fly in a defined search space and their direction is determined by their personal and global best experience. Due to the nonlinear and complicated nature of power system problems, the constraints are difficult to handle. Constraint handling has become very easy in case of PSO as this algorithm searches for the best solution in a predefined search space. Information gathering is done by every particle of the swarm such that position is tracked in a defined area. Parallel searching involved in this technique means none of the swarm gets eliminated in the search process. Search helps in tracing the movement of birds and fishes [26]. Each iteration modifies velocity and position of particle by the help of flowing equation:

$$V_{ij}^{new} = w*(v_{ij}^{r}) + C_1 * R_1 (Pb_{ij}^{best} - P_{ij}^{r}) + C_2 * R_2 (G_j^{best} - P_{ij}^{r}) \tag{3.1}$$

$$P_{ij}^{new} = P_{ij} + V_{ij}^{new} \tag{3.2}$$

where, v_{ij}^{r} is the velocity of i^{th} particle of j^{th} member at r^{th} iteration; P_{ij}^{r} is the current position of j^{th} member of i^{th} particle at r^{th} iteration; R_1 and R_2 are the random variables lies between [0, 1]; C_1 and C_2 are the acceleration coefficients; G_j^{best} is the global best position out of all the best position. 'w' represents inertia weight factor and as the number of iterations increases its value decreases. The equation for 'w' is given as:

$$w = w^{\max} - \left(\frac{w^{\max} - w^{\min}}{r^{\max}}\right) \times r \tag{3.3}$$

Velocity limits are chosen such a way that after each iteration particles acquire a new and improved position that leads it to the target. If the velocity is too high, it is probable that particles may fly off leaving behind the good solutions. Similarly, if its value is too low the particles may not be able to explore the search space well. So it is taken to be between 10-20% of its dynamic range [32].

Particle swarm optimization has so many key features that prove to be very reliable in different applications where conventional optimization techniques might fail as compared to other evolutionary optimization algorithms [31]. The reliability of PSO in comparison with conventional techniques is due to the following key features:

1. It is formed by mathematical and logical functions, by which it can be easily handled.
2. Fewer working parameters are required to be set [8].
3. It works on real integers rather than binary numbers, thus eliminating the conversions.
4. Time and storage requirements are less [16].
5. This technique is preferable to find to find out the globally optimized solution.
6. This technique would result in fast convergence and it also has parallel processing nature [35].
7. It can also provide multiple solutions in a single run [56].

3.2.1 Algorithm for PSO

Step 1: Initialization: The position and velocity of all the particles in a swarm are randomly set within a pre-specified range [18].

Step 2: Velocity Updating: According to the given expression in equation (3.4) the velocity of all are the particles are upgraded.

$$V_{ij}^{new} = w*(v_{ij}^{r}) + C_1 * R_1(Pb_{ij}^{best} - P_{ij}^{r}) + C_2 * R_2(G_{j}^{best} - P_{ij}^{r}) \quad (3.4)$$

where, v_{ij}^{r} is the velocity of i^{th} particle of j^{th} member at r^{th} iteration, P_{ij}^{r} is the current position of j^{th} member of i^{th} particle at r^{th} iteration; 'w' represents inertia weight factor; R_1 and R_2 are the random variables lies between [0, 1]; C_1 and C_2 are the acceleration coefficients; G_{j}^{best} is the global best position out of all the best position [18].

Step 3: Position updating: At each iteration, the positions of all the particles are updated according to the following expression:

$$P_{ij}^{new} = P_{ij} + V_{ij}^{new} \quad (3.5)$$

Step 4: Memory updating: Update the position of a particle with best objective value, when the given conditions are satisfied.

$$P_{ij} = P_{ij}^{best} \text{.............} f(P_{ij}) < f(Pb_{ij}^{best}) \quad (3.6)$$

$$P_{ij} = G_{j}^{best} \text{.............} f(P_{ij}) < f(G_{j}^{best}) \quad (3.7)$$

Step 5: Termination criteria: The algorithm repeats Step 2 to Step 4 until certain stopping rules are satisfied. Once the solution is terminated, the algorithm outputs the optimal fuel cost.

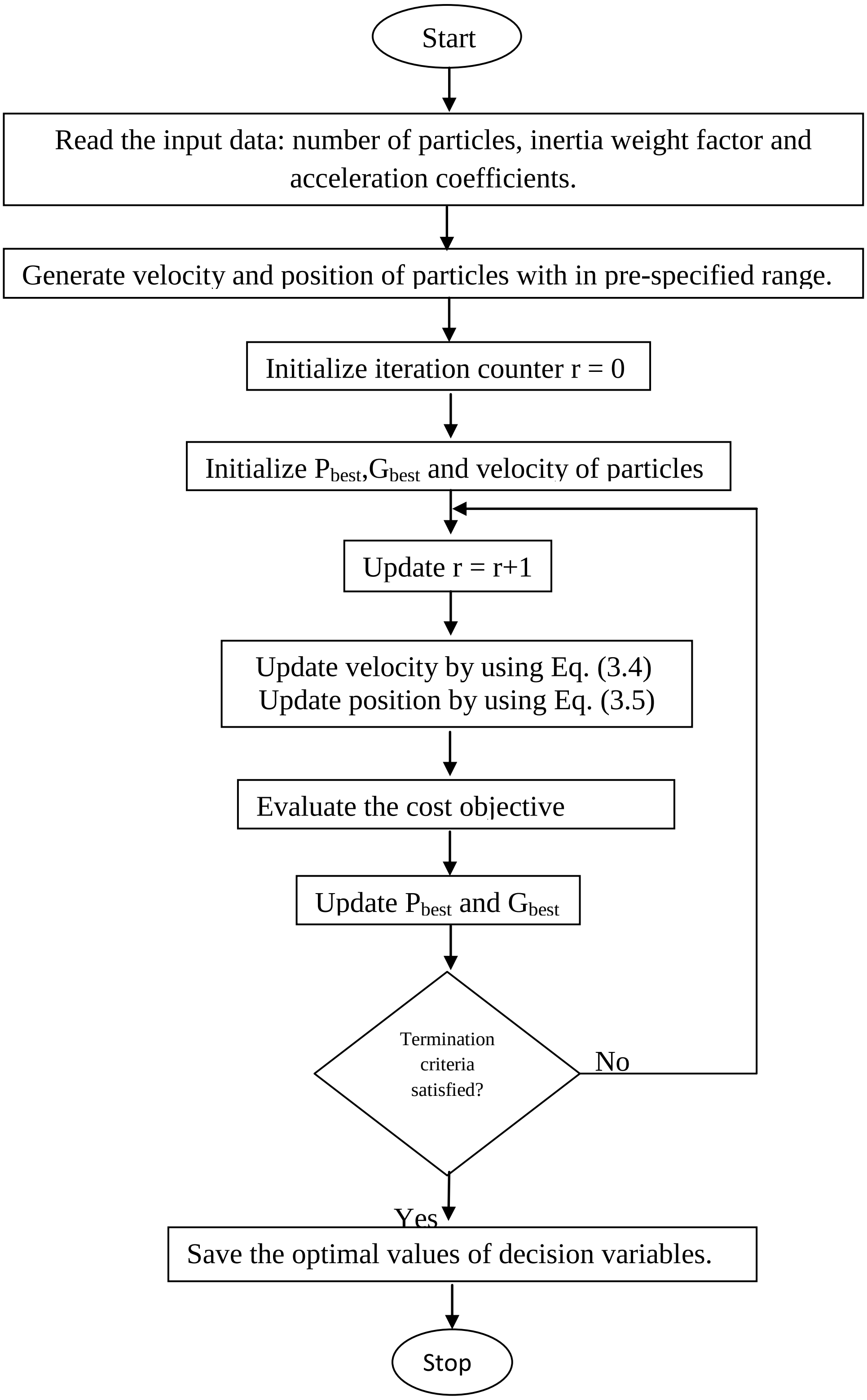

Fig 3.1 Flow chart of basic particle swarm optimization technique [20]

3.2.2 Disadvantages of PSO

Being a powerful optimization technique, PSO has a disadvantage of getting trapped at local minima which make it slow for a global best solution. Some of the disadvantages of PSO are:

1. The velocities are random in nature and are to be chosen suitably otherwise search speed is seriously affected. Either speed becomes too high that particles fly out of the search space, or it becomes so slow that it increases convergence time to a large extent [58].
2. Multiple local minima or heavy constraints in PSO may result in premature convergence [29].
3. Heavy and long problems sometimes lead to its performance deterioration due to an imbalance between exploring and exploiting the search space [41].

3.3 Variations in PSO

PSO is one of the best non-conventional optimization techniques. To solve the various real world problems, PSO and its variants are employed. It is a random search technique in which the position of all the particles in a swarm is randomly initialized in a pre-specified search area. The solution convergence of PSO of depends on upon the inertia weight factor, acceleration coefficients etc. Acceleration coefficient PSO [27] has fixed values in conventional PSO. A new variation is introduced as TVAC; in this approach to obtain the optimal solution cognitive component (C_1) has a lower value than social component (C_2). At each iteration, to obtain the better solution these acceleration coefficients are updated. In Gaussian distribution PSO [28], the problem of parameter dependence is eliminated. In this approach, randomly defined numbers replace the acceleration constant. The main advantage of this enhanced version of PSO is that it improves system convergence and gives better results than classical PSO.

3.3.1 Overview of TVAC-PSO

The scheduling problem of combined heat and power economic dispatch can be solved by modified PSO technique i.e. (time variant acceleration constant particle swarm optimization). The quality of the solution and its convergence depends on upon the acceleration coefficients [30]. The two acceleration coefficient C_1 and C_2 named as cognitive component (C_1) and a social component (C_2) respectively. Higher the value of social component as compared to cognitive component leads particles to best local optimum solution. The value of acceleration coefficient is fixed in conventional PSO [33]. At each iteration, the acceleration coefficients are updated in such a way that cognitive component is reduced and social component is increased [29]. Acceleration coefficients are updated according to the equation (3.8) and (3.9).

$$C_1 = C_{1i} + (\frac{C_{1f} - C_{1i}}{r^{\max}}) \times r \quad (3.8)$$

$$C_2 = C_{2i} + (\frac{C_{2f} - C_{2i}}{r^{\max}}) \times r \quad (3.9)$$

Where C_{1f}, C_{1i}, C_{2f}, C_{2i} are the initial and final acceleration parameter denotes cognitive component and social component respectively. 'r' is the current number of iteration; r^{max} is the maximum number of generations. The followings steps proceed to obtain the optimal solution by using TVAC-PSO [27].

3.3.2 Overview of Gaussian PSO

In Gaussian PSO velocity of each particle of the swarm is modified which updates its local and global best positions. The distance between local best and current position helps in achieving optimal solution easily while the distance between global best and current position exploit the solution for better results [34]. Therefore, better convergence is obtained by modified velocity equation and thus providing a balance between exploring and exploiting the search area. Nonlinear problems can be efficiently solved by modified PSO. Current velocity updates position of particles and distance between local and global best values [38]. In this approach, randomly defined numbers replace the acceleration constant.

$$V_{ij}^{new} = w*(v_{ij}^r) + C_1 * G(\mu, \sigma^2)(Pb_{ij}^{best} - P_{ij}^r) + C_2 * G(\mu, \sigma^2)(G_j^{best} - P_{ij}^r) \quad (3.10)$$

where, v_{ij}^r is the velocity of i^{th} particle of j^{th} member at r^{th} iteration, P_{ij}^r is the current position of j^{th} member of i^{th} particle at r^{th} iteration, 'w' represents inertia weight factor; R_1 and R_2 are the random variables lies between [0, 1], C_1 and C_2 are the acceleration coefficients, G_j^{best} is the global best position out of all the best position, 'G' represents Gaussian distribution function, σ^2 indicates standard deviation which is taken as '1', μ indicates mean which is equal to '0' [25].

Gaussian distribution function is given by:

$$g(x) = (1/\sqrt{2\pi}) \exp^{-x^2/2} \quad (3.11)$$

CHAPTER-4

COMBINED HEAT AND POWER ECONOMIC DISPATCH BY USING MODIFIED PSO

4.1 Introduction

The combined heat and power economic dispatch problems deal with the fact that, the total fuel cost is to be minimized in such a way that all the constraints are satisfied within a feasible operating region. Generally, power system problems deal with such objectives to achieve economic operations. The main problem is to handle constraints. For solving the CHPED problem random search techniques is to be employed [24]. The position and velocity of all the particles are randomly selected within a pre-specified search area. Modified particle swarm optimization is an approach used to solve economic dispatch problems. PSO is a very powerful approach to solving the CHPED problem. The CHPED problem is formulated as an optimization problem including an objective function and its related constraints, expressed as follows:

4.2 Formulation of Objective Function

The scheduling problem includes conventional thermal units, cogeneration units, and heat only units. The main objective function is to minimize the fuel cost, while all other equality and inequality constraints are satisfied. Cost function can be represented by the following expression [47]:

$$f_{\cos t} = \sum_{i=1}^{N_p} C_i(P_i) + \sum_{j=1}^{N_b} C_j(P_j, H_j) + \sum_{k=1}^{N_k} C_k(H_k) \tag{4.1}$$

Subjected to various constraints as discussed in Eq. (2.2) to (2.7) in chapter 2

4.2.1 Equality and inequality constraint handling

PSO is basically unconstraint based searching technique where constraint is handled externally. The uncertainty factors are more prominent in CHP than power dispatch due to fluctuating demand problems. So need arises to fulfill the equality constraints for heat and power using equation (2.2) and (2.3).Accordingly, the error can be computed using the below mentioned equation:

$$E_1(P) = \begin{cases} \sum_{i=1}^{N} (P_i - P_D - P_L)^2); P_D + P_L \neq \sum_{i=1}^{N} P_i \\ 0; P_D + P_L = \sum_{i=1}^{N} P_i \end{cases} \tag{4.2}$$

$$E_1(H) = \begin{cases} \sum_{i=1}^{N} (H_i - H_D)^2); H_D \neq \sum_{i=1}^{N} H_i \\ 0; H_D = \sum_{i=1}^{N} H_i \end{cases} \tag{4.3}$$

By the inequality constraints generation is constraint to lie within its generating limits. Moreover, it is responsible for the satisfactory performance of generating units. However, if the solution exceeds the operational limits then for that case the computation of error is done using below mentioned equation:

$$E_2(P) = \begin{cases} (P_{dp} - P_{dp}^{max})^2; P_{dp} > P_{dp}^{max} \\ (P_{dp}^{min} - P_{dp})^2; P_{dp} < P_{dp}^{min} \end{cases} \tag{4.4}$$

$$E_2(H) = \begin{cases} (H_{dp} - H_{dp}^{max})^2; H_{dp} > H_{dp}^{max} \\ (H_{dp}^{min} - H_{dp})^2; H_{dp} < H_{dp}^{min} \end{cases} \tag{4.5}$$

4.2.2 Feasible operation region constraint

The power and heat demand are mutually dependent upon each other. Thus, it forms the complication in constraint handling. In the case of cogeneration units, the feasible operating region is obtained by keeping the maximum and minimum value of heat and power units within an allowable range [38]. Feasible operating region is nothing but a graphical representation, which shows a variation of power with heat and vice-versa. If the shape is irregular, then it is more complex to obtain feasible area within the curve. A quadrilateral which is irregular in shape denotes typical feasible operating region and is represented in figure (4.1) [42].

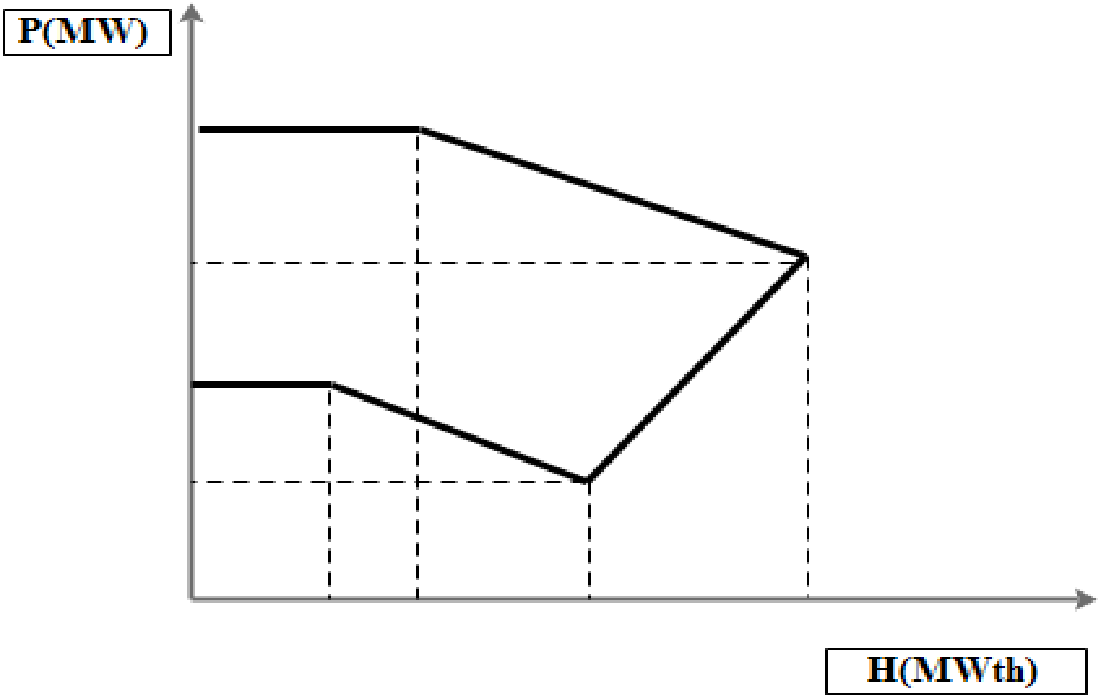

Figure 4.1 Feasible operating regions for cogeneration unit [22]

The objective function also includes Euclidean distance based penalty factor so that constraint handling becomes easy and remains within the feasible operating region [44]. If (H_o, P_o) represents the output position of cogeneration unit and (aH+bP+c=0) represents the equation of a straight line. The shortest distance from that point to the line is calculated by using the equation given below:

$$d=\frac{|aH_o+bP_o+c|}{\sqrt{a^2+b^2}} \qquad (4.6)$$

Then penalty factor is calculated which act as an error for the bound violation and can be evaluated using equation as follows:

$$E(P,H)=\sum_{i=1}^{N} d_i \qquad (4.7)$$

The sum of distance between the violated boundaries i.e. (d1 and d2) calculate the error, where (H1, P1) are the corner point lies at the boundary limit as shown in figure (4.2).

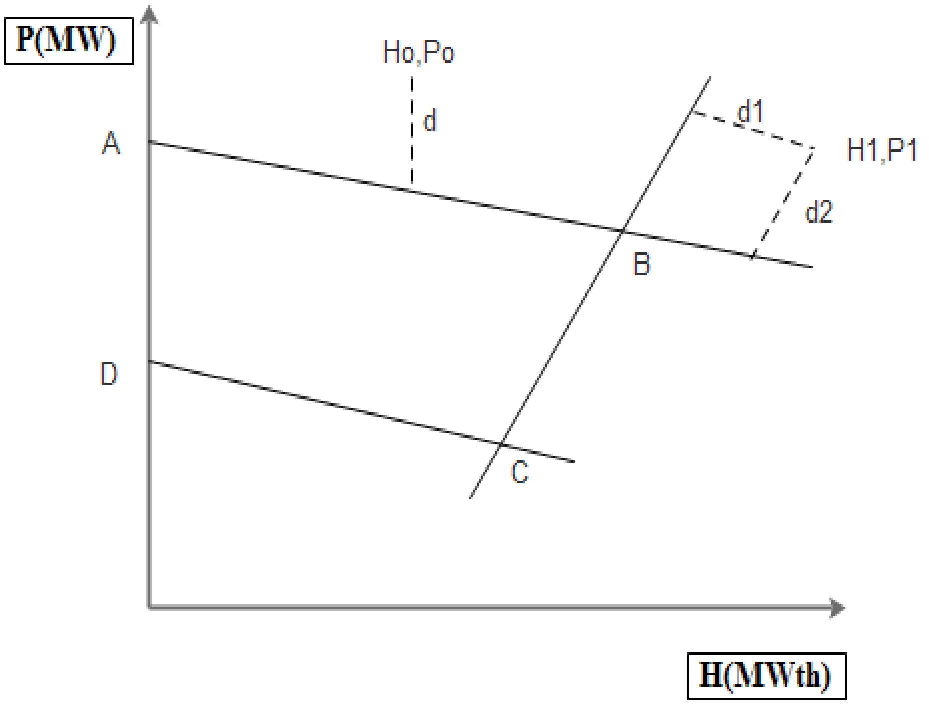

Fig 4.2 Feasible operating region indicating Euclidean distance penalty based approach [34]

4.2.3 Objective Function Evaluation

For the purpose of judging the implemented technique on CHPED problem, an objective function consists of overall generation cost in addition to the penalty factor is minimized, so that all the constraints are satisfied and result obtained within feasible operating region. The main objective of this problem is to minimize the function value represented as OF (P, H) [54].

$$OF\ (P,\ H)\ =\ f_{cost}\ (P,\ H)\ +\ r\ \times\ error \tag{4.8}$$

where, error = E1 (P) + E1 (H) + E2 (P) + E2 (H) + E (P, H) and ‘r’ represent a penalty factor.

4.2.4 Algorithm for Gaussian PSO

Step1 Parameter selection

The parameters used in PSO such as population size, the boundary constraints, acceleration factor, inertia weight factor, the maximum number of iterations to be carried out are selected.

Step2 Initialization

The position and velocity of all the particles in a swarm are randomly set within pre-specified range based on maximum and minimum operating limits such that all the inequality constraints should be satisfied [32].

Step 3: Velocity Updating

In this step, the new velocity of particles can be calculated with the introduction of a new variable called Gaussian distribution function.

$$V_{ij}^{new} = w*(v_{ij}^{r}) + C_1 * G(\mu, \sigma^2)(Pb_{ij}^{best} - P_{ij}^{r}) + C_2 * G(\mu, \sigma^2)(G_j^{best} - P_{ij}^{r}) \quad (4.9)$$

where, v_{ij}^{r} is the velocity of i^{th} particle of j^{th} member at r^{th} iteration, P_{ij}^{r} is the current position of j^{th} member of i^{th} particle at r^{th} iteration, 'w' represents inertia weight factor, R_1 and R_2 are the random variables lies between [0, 1], C_1 and C_2 are the acceleration coefficients, G_j^{best} is the global best position out of all the best position, 'G' represents Gaussian distribution function, which is given by following expression in equation (4.10), σ^2 indicates standard deviation which is taken as '1', μ indicates mean which is equal to '0' [25].

$$g(x) = (1/\sqrt{2\pi})\exp^{-x^2/2} \quad (4.10)$$

Step 4: Position updating

At each iteration, the positions of all the particles are updated according to the following expression:

$$P_{ij}^{new} = P_{ij} + V_{ij}^{new} \quad (4.11)$$

Step 5: Checking the updated values for bound violations:

The dimension of conventional units is checked for all the limit violation. Because there is a chance to violate the minimum and maximum limits after each updating process. If the solution is not in the feasible operating region, nearest best value at the boundary is to be set [35].

Step 6: Updating the best local values for each generating unit

In this step, the local best position of all the particles is updated for scheduled generating units, which includes conventional power units, co-generation units, and heat-only units. Thus, the solution obtained gives the best optimal fuel cost.

Step7: Stopping criterion

Stopping criteria are based on a maximum count of iteration. If all the conditions are not satisfied, then above algorithm approach is repeated from step 2. The minimum fuel cost of all the generating units makes the solution optimal [36].

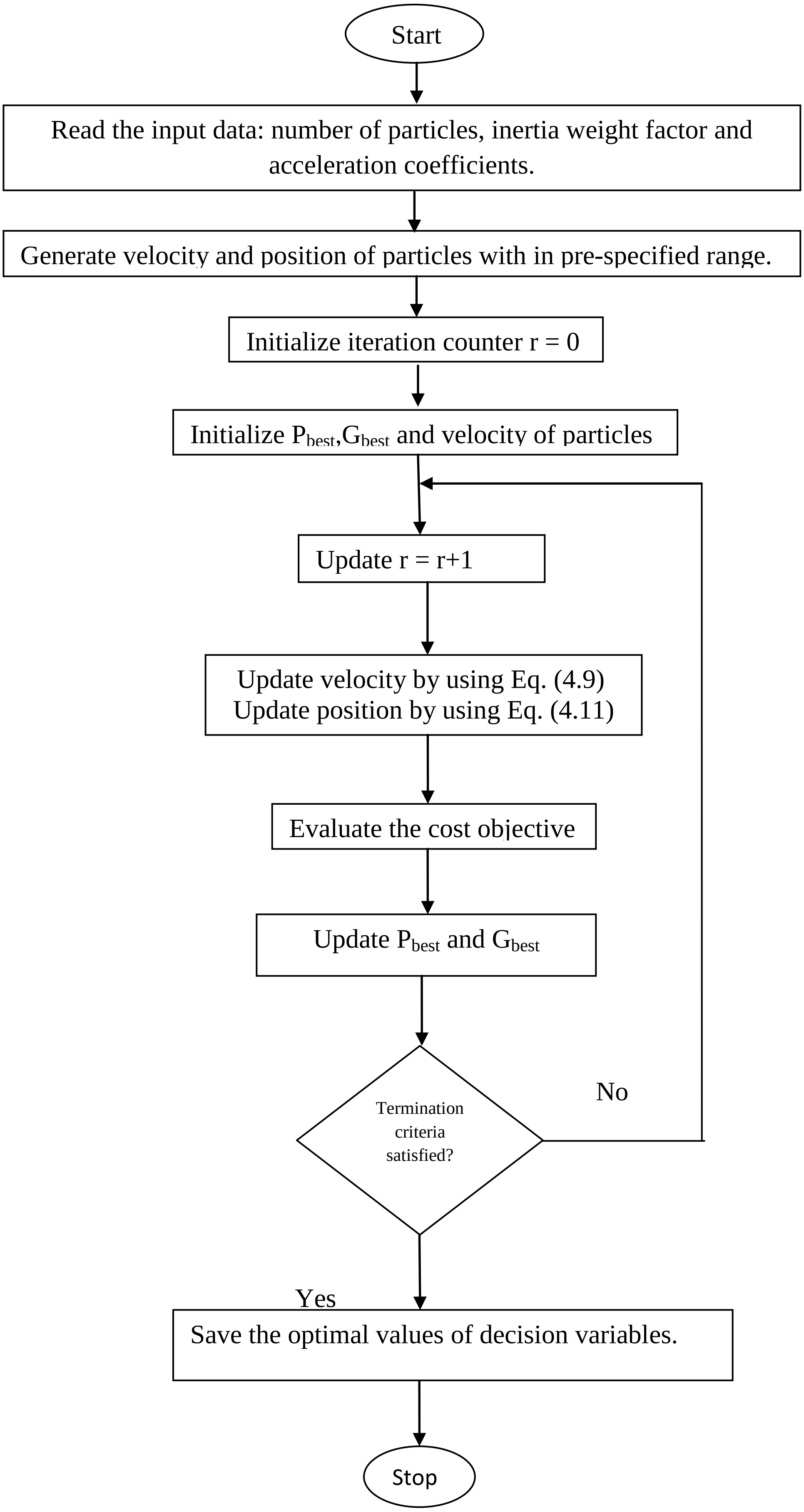

Fig 4.3 Flow chart for Gaussian particle swarm optimization technique

4.3 Time variant acceleration coefficient-Particle Swarm Optimization

The optimal solution of combined heat and power economic dispatch can be obtained by modified PSO technique i.e. (time variant acceleration constant particle swarm optimization). The quality of the solution and its convergence depends on upon the acceleration coefficients [30]. The two acceleration coefficient C_1 and C_2 named as cognitive component (C_1) and a social component (C_2) respectively. Higher the value of social component as compared to cognitive component leads particles to best local optimum solution. The value of acceleration coefficient is fixed in conventional PSO [33]. At each iteration, the acceleration coefficients are updated in such a way that cognitive component is reduced and social component is increased [29].

$$C_1 = C_{1i} + (\frac{C_{1f} - C_{1i}}{r^{\max}}) \times r \tag{4.12}$$

$$C_2 = C_{2i} + (\frac{C_{2f} - C_{2i}}{r^{\max}}) \times r \tag{4.13}$$

Where C_{1f}, C_{1i}, C_{2f}, C_{2i} are the initial and final acceleration parameter denotes cognitive component and social component respectively. ‘r’ is the current number of iteration; r^{max} is the maximum number of generations. The followings steps proceed to obtain the optimal solution by using TVAC-PSO [27].

4.3.1 Algorithm for TVAC-PSO

Step1: Parameter selection

The parameters used in PSO such as population size, the boundary constraints, acceleration coefficients (C_{1f}=2.5, C_{1i}=0.5, C_{2f}=2.5, C_{2i}=0.5), inertia weight factor, the maximum number of iterations to be carried out are selected.

Step2: Initialization

The position and velocity of all the particles in a swarm are randomly set within pre-specified range based on maximum and minimum operating limits such that all the inequality constraints should be satisfied [29].

Step 3: Velocity Updating: In this step, the velocity of particles can be calculated by using equation (4.14) given below:

$$\begin{aligned} V_{ij}^{new} &= w*(v_{ij}^{r}) + C_{1i} + (\frac{C_{1f} - C_{1i}}{r^{\max}}) \times r \times R_1 (Pb_{ij}^{best} - P_{ij}) \\ &+ C_{2i} + (\frac{C_{2f} - C_{2i}}{r^{\max}}) \times r \times R_2 (G_{j}^{best} - P_{ij}) \end{aligned} \tag{4.14}$$

Where v_{ij}^{r} is the velocity of i^{th} particle of j^{th} member at r^{th} iteration, P_{ij}^{r} is the current position of j^{th} member of i^{th} particle at r^{th} iteration, 'w' represents inertia weight factor, R_1 and R_2 are the random variables lies between [0, 1], G_{j}^{best} is the global best position out of all the best position; 'r' is the current number of iteration, r^{max} is the maximum number of generations, C_{1f}, C_{1i}, C_{2f}, C_{2i} are the initial and final acceleration parameter [28].

Step 4: Position updating

At each iteration, the positions of all the particles are updated according to the following expression:

$$P_{ij}^{new} = P_{ij} + V_{ij}^{new} \tag{4.15}$$

Step 5: Checking the updated values for bound violations

The dimension of conventional units is checked for all the limit violation. Because there is a chance to violate the minimum and maximum limits after each updating process. If the solution is not in the feasible operating region, nearest best value at the boundary is to be set.

Step 6: Updating the best local values for each generating unit

In this step, the local best position of all the particles is updated for scheduled generating units, which includes conventional power units, co-generation units, and heat-only units. Thus, the solution obtained gives the best optimal fuel cost [34].

Step7: Stopping criterion

Stopping criteria are based on a maximum count of iteration. If all the conditions are not satisfied, then above algorithm approach is repeated from step 2. The minimum fuel cost of all the generating units makes the solution optimal.

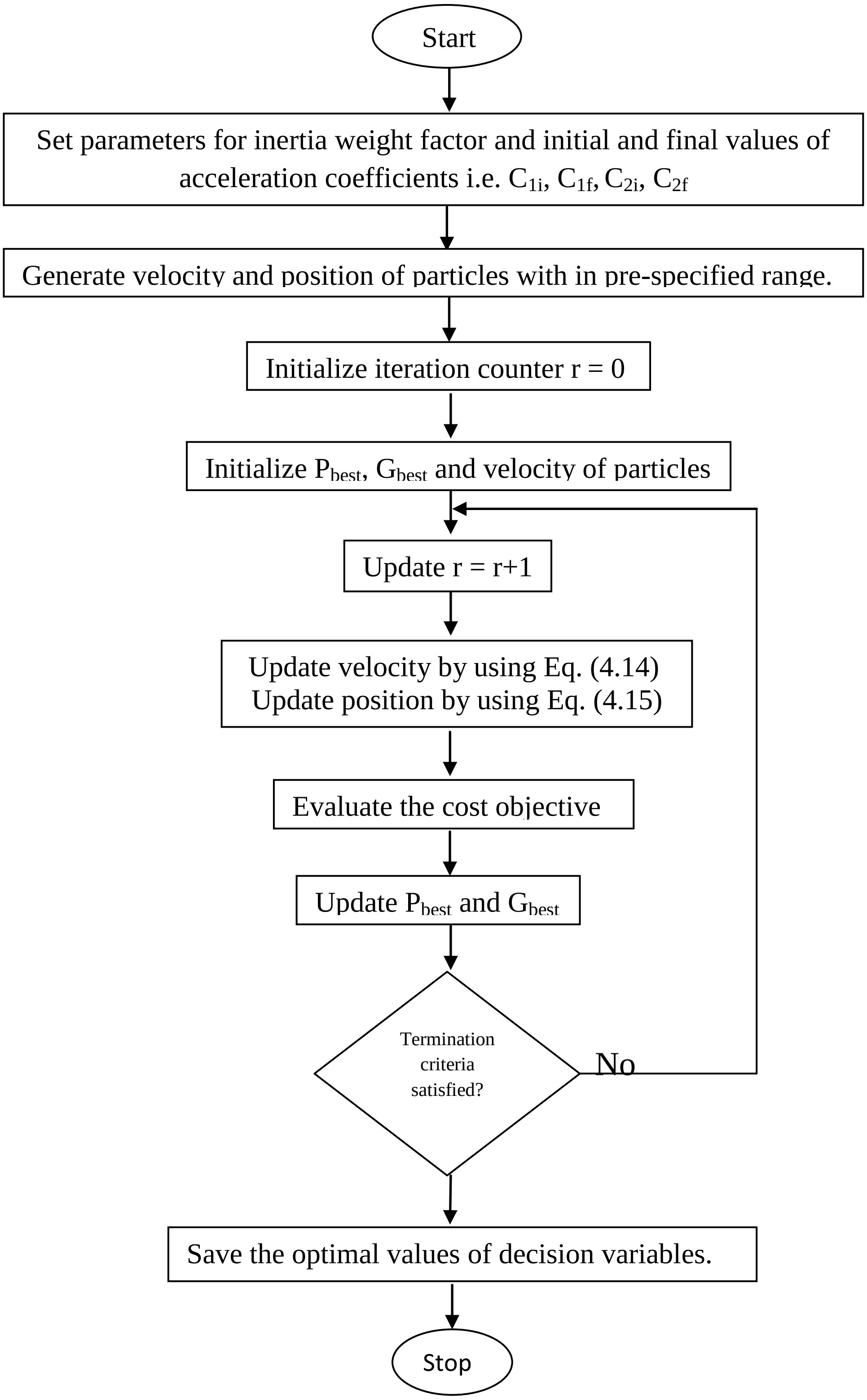

Fig 4.4 Flow chart for time variant acceleration coefficient-PSO technique

CHAPTER-5

RESULTS AND DISCUSSION

5.1 Introduction

The sound knowledge of Combined Heat and Power Economic Dispatch by using modified PSO has been discussed in previous chapters. For scheduling, the generation of CHPED problem, the algorithm of modified PSO is implemented [26].

5.2 Case Study

The PSO technique has been implemented on a sample test system. The case-1 has been studied for 4 generating units including 1 conventional thermal unit, 2 cogeneration units, and 1 heat-only unit [62]. Input data is given in Appendix-A.

To solve the CHPED problem, a sample test system having four generating units is considered. This system includes only one thermal unit, two cogeneration units, and one heat-only unit. The total power demand for the power unit and heat unit are 200 MW and 115 MWth [62]. The operating limits of cogeneration units for feasible operation region are mentioned in fig 5.1 and 5.2. The input data for the test system along with cost coefficients are given in table A.1 of appendix A.

5.3 Simulation Results

This research work has been performed in FORTRAN-90 for solving CHPED problem by using modified PSO. In order to obtain an optimal solution within a feasible operating region, different values of PSO parameters are taken. PSO parameters include acceleration constants, maximum and minimum inertia weight and a maximum no. of iterations. These parameters have been set for an optimally best solution. The solution is obtained for 50 particles and 1500 iterations.

Table 5.1 Parameter settings of Modified PSO

S. No.	Parameter	Value
1	Swarm Size	50
2	Inertia Weight Factor	W_{max}=0.9 and w_{min}=0.4
3	Acceleration Coefficients	C_{1i}=0.5, C_{1f}=2.5 C_{2i}= 0.5,C_{2f}= 2.5

The test system involved consists of one thermal unit, two combined units (heat and power units), and one heat only unit. Figure 5.1 and 5.2 shows the operating limits of the cogeneration system.

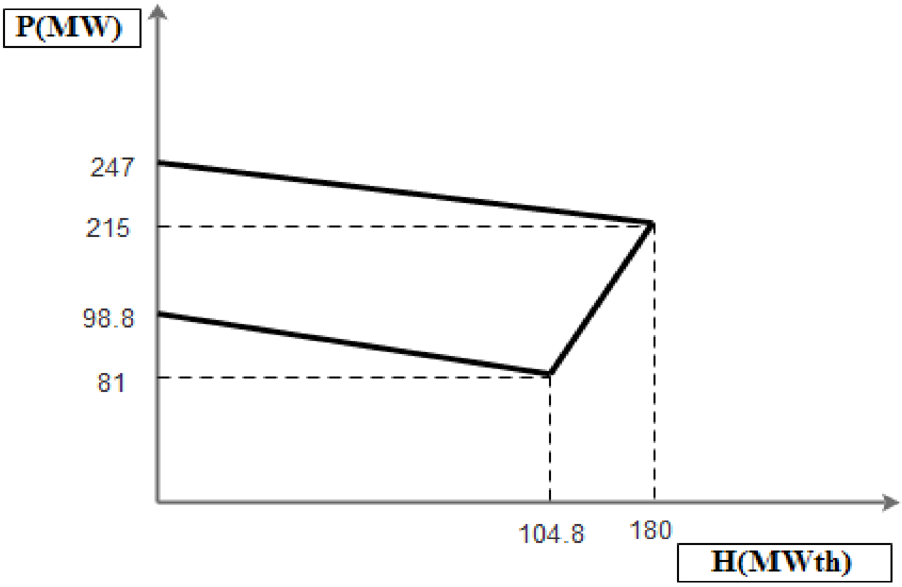

Fig 5.1 Feasible operating region for cogeneration unit 1 of case study [38]

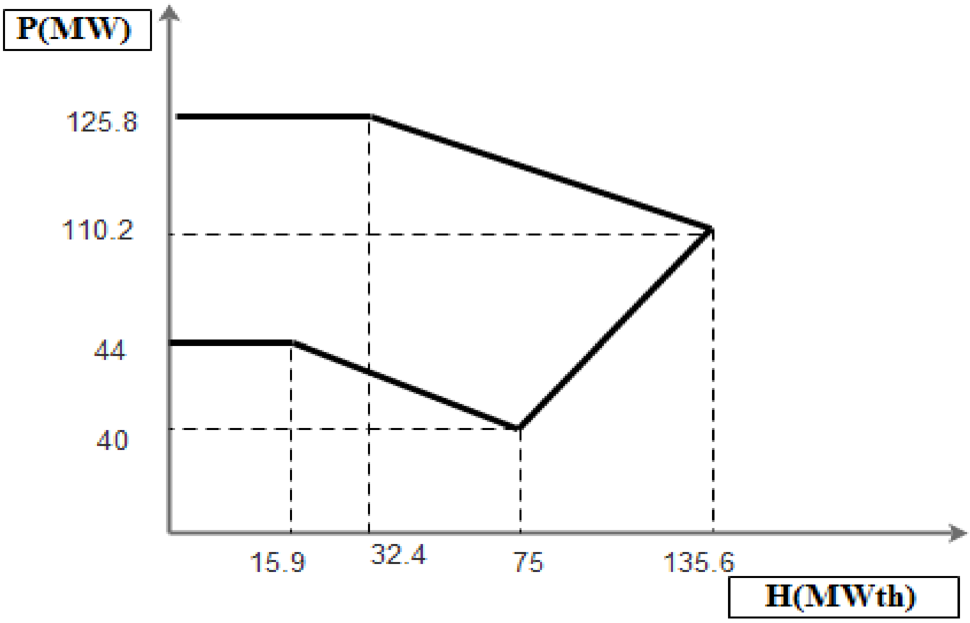

Fig 5.2 Feasible operating region for cogeneration unit 2 of case study [38]

Conventional PSO and different modified PSO's are applied to a test case and comparison of results is done on the same test system. Different modified PSO's used here are TVAC-PSO and Gaussian PSO. It is seen that the results obtained from Gaussian PSO are more satisfactory as compared to other approaches. The power generations by each of the generating unit i.e. power, heat and combined heat and power were obtained from different techniques and Table 5.2 illustrates the results.

Table 5.2: Results obtained by comparing different techniques

	PSO	TVAC- PSO	Gaussian PSO	ACO [62]
P1(MW)	1.892090E-02	9.233093E-02	2.167969E-01	0.08
P2(MW)	188.230200	149.516600	157.001200	150.93
P3(MW)	61.750920	50.391040	43.000050	49.00
H4(MWth)	5.153732E-01	6.442337E-01	7.451172E-01	48.84
H5(MWth)	32.233830	29.097030	33.106050	65.79
H6(MWth)	82.250790	85.258740	81.148830	0.37
Cost($)	9559.484	9362.688	9270.729	9452

From table 5.2, it is concluded that results obtained by Gaussian PSO is overcome the results obtained by PSO, TVAC-PSO and ACO [62]. It is also evident from table 5, that scheduled power and heat satisfy also constraints.

CHAPTER-6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

In this research work Combined Heat and Power Economic Dispatch problem has been solved by Modified PSO. This method successfully searches the optimal solution for ED problem within a feasible operating region. It is seen that constraint handling with PSO is difficult due to the interdependence of heat and power demands. The objective function also includes Euclidean distance based penalty factor so that constraint handling becomes easy and remains within the feasible operating region. Results show the effectiveness of used algorithm when compared with other techniques while handling large-scale problems in the power system.

The research work draws following conclusions:

1. The use of exterior penalty factor helps in handling qualitative constraints.
2. The obtained results including all constraints are satisfying.
3. Results obtained from Gaussian PSO are effective and better when compared to TVAC and conventional PSO.

6.2 Scope of future work

The extension to the proposed work can help in the improvement of results and is summarized as follows:

1. The above-mentioned technique can be helpful in solving hydrothermal or reactive power problems.
2. Multi-objective problems can be handled by these meta-heuristic techniques in the best way.

LIST OF PUBLICATIONS

National Conference

Presented and published a paper in “National Conference on Advance Science and Technology in Electrical Engineering”.

1. S. Jain and N. Narang, “A review on combined heat and power economic dispatch”, National Conference on Advance Science and Technology in Electrical Engineering, RIMT, Gobindgarh, Punjab, 2016.

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APPENDIX-A

Table A.1 System Data for Case Study

Conventional Power Unit

Unit	P_{min} (MW)	P_{max} (MW)	a_i ($/MW^2)	b_i ($/MW^2)	c_i ($)	d_i ($)	e_i (rad/MW)
1	0	150	0	50	0	0	0

Cogeneration Unit

Unit	P_{min} (MW)	P_{max} (MW)	H_{min} (MWth)	H_{max} (MWth)	a_i ($/MW^2)	b_i ($/MW^2)	c_i ($)	d_i ($)	e_i (rad/MW)	f_i ($)
2	81	247	0	180	2650	14.5	0.345	4.2	0.3	0.3
3	40	125.8	0	135.6	1250	36	0.43	0.6	0.27	.01

Conventional Heat Unit

Unit	H_{min} (MWth)	H_{max} (MWth)	a_i ($/MW^2)	b_i ($/MW^2)	c_i ($)	d_i ($)	e_i (rad/MW)
4	0	2695.2	0	0	0	23.4	0

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II. <u>Educational Qualification</u>

Degree	**Subject**	**Institute/ Board**	**Marks (%)**
S.S.C	Science	C.B.S.E.	70%
H.S.C.	PCM	C.B.S.E.	70%
B.Tech.	EEE	Krukshetra University	71% (hons.)

III. <u>List of Publications</u>

1. S. Jain and N. Narang, "A review on combined heat and power economic dispatch", National Conference on Advance Science and Technology in Electrical Engineering, RIMT, Gobindgarh, Punjab, 2016.

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