Combined Heat and Power Economic Dispatch Using Differential Evolution

A Dissertation

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CERTIFICATE

This is to certify that the dissertation entitled **"Combined Heat and Power Economic Dispatch using Differential Evolution"** is an authentic record of my own work carried out as per requirements for the award of degree of **Master of Engineering** in **Power Systems & Electric Drives** submitted in Electrical and Instrumentation Engineering Department at Thapar University, Patiala, under the guidance of **Mr. Nitin Narang, Assistant Professor (EIED).**

The matter in this dissertation has not been submitted for the award of any other degree of this or any other university.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

The economic dispatch problem is one of the important issues in power system. The objective of the combined heat and power economic dispatch is to find the optimal point of power and heat generation with minimum fuel cost while satisfying both heat and power demands and other constraints.

In this dissertation work, differential evolution search technique is implemented to solve the combined heat and power economic dispatch problem with bounded feasible operating region. In this work, the feasible region constraint is handled using exterior penalty factor. The optimal utilization of multiple combined heat and power systems is a complex problem. In order to show the effectiveness of this technique, the proposed approach is applied to three test systems.

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CHAPTER 1. INTRODUCTION

1.1 Overview

There is sharp rise in energy demand which results in increased pollution. Due to this, issues of energy conservation and green power gained much attention in 21st century. The conversion of primary fossil fuels, such as coal and gas, to electricity is a relatively inefficient process. Even the most modern combined cycle plants can only achieve efficiencies in between 50–60%. Most of the energy that is wasted in this conversion process is released to the environment as waste heat. The principle of combined heat and power (CHP), also known as cogeneration, is to recover and make beneficial use of this heat, which raise the overall efficiency of the conversion process [1]. The very best CHP schemes can achieve fuel conversion efficiencies of the order of 90%. The energy saving potential as well as less green house gas emission due to the wise use of cleaner fossil fuels burned in CHP units, like natural gas, give them advantage from conventional power systems.

Cogeneration systems have now been extensively utilized by the industry. The industries with necessities of both heat and power can supply its own demands with CHP systems.CHP systems can be constructed in urban areas and used as distributed electrical energy sources. To obtain the optimal utilization of CHP units, economic dispatch (ED) must be applied for more energy saving. The objective of economic dispatch is to schedule the outputs of the online generating units so that the fuel cost of generation can be minimized, while simultaneously satisfying all unit and system equality and inequality constraints. Some complications arise in CHP systems because the dispatch has to find the set points of power and heat production with the minimum fuel cost such that both demands were matched, indeed, the CHP units should operate in a bounded power vs. heat plane.

In the past, a wide variety of evolutionary algorithms (EA's) have been used to solve ED problems. In this thesis work one of the most recent heuristic techniques differential evolution (DE) is used. DE is a simple evolutionary algorithm, introduced by Storn and Price in 1995 [2], which consistently found the optimal solution and often with fewer function evaluations than the other direct search methods. DE has been very successful in the solution of a variety of ED problems in which it has shown a great robustness and a very fast convergence.

The highlights of DE are:

- A population of solution vectors is successively updated by addition, subtraction, and component swapping, until the population converges, hopefully to the optimum.

- No derivatives are used.
- Very few parameters to set.
- A simple and very reliable method

These are precisely the characteristics of DE that make it attractive to solve combined heat and power economic dispatch (CHPED) problems [3].

1.2 Literature Review

Despite extensive research in the field of the CHPED from the past two decades, much of the efforts still today have involved so as to obtain the most optimal dispatch at most optimal cost.

Initial techniques were developed based on the separability of the objective function of the problem. An algorithm was developed by Rooijers and Van Amerонge [4] related with two level strategies, in which the lower level was presented to solve the given power and heat lambdas, and the upper level updates the lambda's sensitivity coefficients. The procedure is repetitive until the heat and power demands are met. Guo, *et al*. [5] worked on algorithm for CHPED problem in which the problem is decomposed into two sub- problems:"heat dispatch and the power dispatch". In this work, the interpretation leads to the growth of two-layer algorithm. The outer layer uses the Lagrangian relaxation (LR) technique to solve the power dispatch, and the inner layer uses the gradient searching method to solve the heat dispatch with the unit heat capacities passed by the outer layer. Rao [6] developed a direct solution for the CHPED problem in which he created a formula for the system lambdas corresponding to the power and heat demands in terms of the coefficients of the generator cost function. Recalculation of the system lambda was also required to eliminate power and heat mismatches. Chapa and Galaz [7] present an algorithm to solve the ED problem for CHP systems. The algorithm takes the basis of sequential quadratic programming algorithms used to solve nonlinear optimization problems and the logic of the LR technique, but instead of considering linear inequality constraints, it temporary erase them from the problem, making the problem easier. Tan, *et al.* [8] introduced a much simplified, flexible and efficient LR technique for the CHPED problem. The method is divided into two optimization levels known as lower and upper levels. The upper level solves for the global constraints where else the lower level deals with the optimization of individual units. This method provides flexibility for separable problem in which different, simple and effective techniques could be used to solve the lower level sub-problems for optimal solutions.

Wong and Algie [9] develop an EP based algorithm for the CHPED problem for cogeneration systems. Random initialization and constraint relaxation for the feasible operating region of the cogeneration units have also been developed. In this method, the expressions for the standard deviation used in the mutation process have been designed such that the size of the mutation search range can be controlled and the neighborhood of the best individual in a population be searched. Tyagi and Pandit [10] formulated CHPED problem of a system by using Particle swarm optimization (PSO) to determine the unit heat and power production so that production cost is minimized. Vasebi [1] introduced a harmony search algorithm to solve the CHPED problem. The results obtained by the proposed method reveal that the proposed algorithm can find better solutions when compared to conventional methods and is an efficient search algorithm for CHPED problem. Basu [11] presents a novel optimization approach to the CHPED problem by using bee colony optimization algorithm. The algorithm is a swarm-based algorithm inspired by the food foraging behavior of honey bees. Basu [12] presents artificial immune system algorithm for solving the CHPED problem. Artificial immune system is based on the clonal selection principle which implements adaptive cloning, hyper-mutation, aging operator and tournament selection. Sinha, *et al.* [3] investigates the performance of DE for solving CHPED problems in power systems. In this work, a DE based algorithm has been developed for solving the CHPED problem considering quadratic function together with valve point loadings for the electrical power generating units. Song, *et al.* [13] improves search methodology based on a distributed autocatalytic process, called the ant colony search algorithm (ACSA), and applied to the CHP economic dispatch problem. The main characteristics of the ACSA are positive feedback, distributed computation and the use of a constructive greedy heuristic.

Su and Chiang [14] proposed an improved genetic algorithm (IGA) with multiplier updating (MU) which integrates the IGA and the MU such that it is efficient for large-scale CHPED problems. In this work, the IGA efficiently searches the optimal solutions in the economic dispatch process and the MU effectively handles the heat–power feasible region constraints. The proposed algorithm integrates the IGA and the MU such that it has the merits of automatically adjusting the randomly given penalty to a proper value and requiring only a small-size population. Tyagi and Pandit; Rabiee, *et al.* [15][16] have introduced the Time Varying Acceleration Coefficients PSO approach for solving the CHPED problems. The thought behind this approach is to improve the seeking ability of the classical PSO and to use a parameter automation strategy for appropriate balance between local and global search. This algorithm is very stable and consistent. Chen, *et al.*[17] proposed a novel approach based on the direct search method for the solution of CHPED problem. In this method, in order to increase the possibility of exploring the search space where the global optimal solution exists, another effective strategy based on a successive refinement search technique is also proposed to guarantee a possibly complete examination of the solution space. Wang and Singh [18] first formulated the stochastic model for CHP dispatch, and then an improved PSO method is developed to deal with the economic CHP dispatch by simultaneously considering multiple conflicting objectives. Ramezani [19] proposed a optimization approach based on improved differential evolution (IDE) to solve the CHPED problem. According to the author, the evolutionary mechanism of the IDE is more effective than the original DE and it has the advantage of being easy to comprehend, simple to implement so that it can be utilized for a wide variety optimization problems. Song and Xuan [20] employed an improved penalty function formulation for the Genetic Algorithm (GA) to solve the CHPED problem. The proposed approach uses an improved penalty function formulation for GA in which the penalty factors can be adaptively adjusted during the evolution process to effectively solve constrained optimization

Sudhakaran and Slochanal [21] employed a hybrid of GA with tabu search and applied it to a four-unit system. The proposed method is developed in such a way that a simple GA is acting as a base level search to direct the search towards the optimal region and local searches synergistically combined with tabu search is next employed to fine tune the search to reach the optimal solution. Chang and Fu [22] used a multi-objective method by using a fuzzy decision index and GA to a seven generator sample system. Three objectives, namely: the total generation cost, the expected power generation deviation and the expected heat generation deviation of the system, are minimized in this study. Sabramooz, *et al.*[23] addressed a comparative meta-heuristic and mathematical optimization approach, to illustrate the weakness and strength of the optimization techniques in solving a large-scale optimization problem. Gandomi, *et al.*[24] presented an optimization technique, namely mesh adaptive direct search to solve the CHPED problem with bounded feasible operating region. In this work, the Latin hypercube sampling, PSO and design and analysis of computer experiments surrogate algorithms are used as search strategies to solve each of the CHPED problems.

Differential evolution is one of the most prominent new generation EAs, proposed by Storn and Price [2], for minimizing possibly nonlinear and non-differentiable continuous space functions. Authors demonstrated that this method converges faster and with more certainty. Sinha, *et al.* [3] developed a DE based algorithm for solving the CHPED problem considering quadratic function together with valve point loadings for the electrical power generating units. Mezura-Montes, *et al.* [25] presented a DE based approach to solve constrained optimization problems. In this approach, each solution is allowed to generate more than one offspring but using a different mutation operator which combines information of the best solution in the population and also information of the current parent to find new search directions. Noman and Iba [26] by using the concepts of existing schemes in evolutionary computation, proposed a model for generation alternation in DE. This model locates the global minimum at a higher convergence velocity. In this work, by selecting parents for breeding and offspring for survival, DE's search capability gets further accelerated, which will be particularly useful for expensive function optimizations. Kukkonen and Lampinen [27] present DE as a population based, stochastic function optimizer using vector differences for perturbing the population. They observed that constraint handling method of DE decreases the actual number of needed objective and constraint function evaluations, and therefore more generations or solution candidate evaluations could be performed. Abido, *et al.* [28] developed a DE algorithm to solve emission constrained ED problem. The proposed algorithm attempts to reduce the production of atmospheric emissions such as sulfur oxides and nitrogen oxides which is achieved by including emissions as a constraint in the objective of the overall dispatching problem. Lampinen and Zelinka [29] proposed an approach based on DE algorithm which is capable of optimizing all integers, discrete and continuous variables and capable of handling non-linear objective functions with multiple non-trivial constraints. Zhao, *et al.* [30] proposed a DE algorithm for constrained optimization problem based on multi-objective constraint handling. This proposed algorithm can achieve global search and local search effectively by using of the DE algorithm whose main feature is converting constraints into a target, and converts the problem into two-objective optimization problem. Noman and Iba [31] studied DE algorithm and in this approach, an improved way of satisfying the power balance constraint is proposed and other boundary constraints were satisfied using a reflection mechanism that is commonly used in constrained optimization with DE. Krohling, *et al.* [32] proposed a sequential DE algorithm to solve constrained min–max optimization problems. Authors used an adaptive penalty approach to handle the constraints. Babu and Jehan [33] presented DE algorithm which is used for solving two problems: (I) a multi-objective optimization problem (with two objective functions to be maximized) using penalty function method and weighing factor method and (2) classical Himmelhlau function. Datta and Dutta [34] proposed a DE algorithm for scheduling of units, and it is incorporated with some other techniques for determining the amounts of power to be generated by committed units. In order to satisfy power balance equality constraint, authors proposed a binary-real-coded DE, in which the binary part deals with the scheduling of units and the real part determines the amounts of power generated by committed units. Chiou [35] presented a hybrid differential evolution method using the parallel processors of the two-membered evolution strategy. In this way, the global search ability for this method can be inspected. To accelerate the search for the global solution, the concept of the variable scaling factor based on the one-fifth success rule of evolution strategies is embedded in the original method. Basu [36] presented a novel approach based on DE for solving the CHPED problem. Computation time, simplicity and its capability of handling a wide class of optimization problems are key advantages of this technique.

1.3 Objective of the Work

The Differential Evolution search technique is applied to find optimum solution of CHP units. The objective of CHP problem is to minimize cost subjected to equality constraints and inequality constraint. Equality constraint comprises power and heat balance condition. Inequality constraint comprises limit on power and heat and feasible area constraint between power and heat.

1.4 Organization of Dissertation

The dissertation has been summarized in six chapters. The chapter 1 highlights the brief introduction, brief literature review and scope of the work. The chapter 2 highlights the topic combined heat and power economic dispatch. The chapter 3 explores the structure of differential evolution, its overview aspects and its methodology. The chapter 4 presents the solution approach to combined heat and power economic dispatch problem using differential evolution algorithm. The chapter 5 presents the results pertaining to various test systems. The chapter 6 presents the conclusion and also presents the scope for future work followed by reference section.

CHAPTER 2. COMBINED HEAT AND POWER ECONOMIC DISPATCH

2.1 Introduction

Combined heat and power generation is a mature and established technology. It has higher energy efficiency and less green house gas emission compared with the other forms of energy supply. The essential difference between CHP units and conventional condensing plant is in the type of the power obtained and the overall efficiency of each plant. In conventional condensing plants, the energy from the fuel is utilized to produce electrical power only, while in CHP systems, the energy from the fuel is utilized to produce both electrical and thermal power thus increasing its efficiency. The conventional condensing plant delivers power at an efficiency of 35–55%. Using efficient flue gas condensation, the total efficiency of CHP unit is found to be in the range of 80–111% (lower heating value base).The heat production depends on power generation and vice versa. This introduces complexity due to the non-separable heat in the CHP units and nature of electrical power. Economic dispatch problem of CHP plants is more complicated problem in comparison to power unit dispatch due to two-dimensional nature of the problem [37].

CHP systems are normally classified according to the sequence of energy use and the operating schemes adopted. On this basis CHP systems can be classified as either a topping or a bottoming cycle which are explained as below:

Topping cycle

In a topping cycle, the fuel supplied is used to first produce power and then thermal energy, which is the by-product of the cycle and is used to satisfy process heat or other thermal requirements. Topping cycle CHP system is widely used and is the most popular method of cogeneration.

Bottoming cycle

In a bottoming cycle, the primary fuel produces high temperature thermal energy and the heat rejected from the process is used to generate power through a recovery boiler and a turbine generator. Bottoming cycles are suitable for manufacturing processes that require heat at high temperature in furnaces and kilns, and reject heat at significantly high temperatures. Typical areas of application include cement, steel, ceramic, gas and petrochemical industries. Bottoming cycle plants are much less common than topping cycle plants.

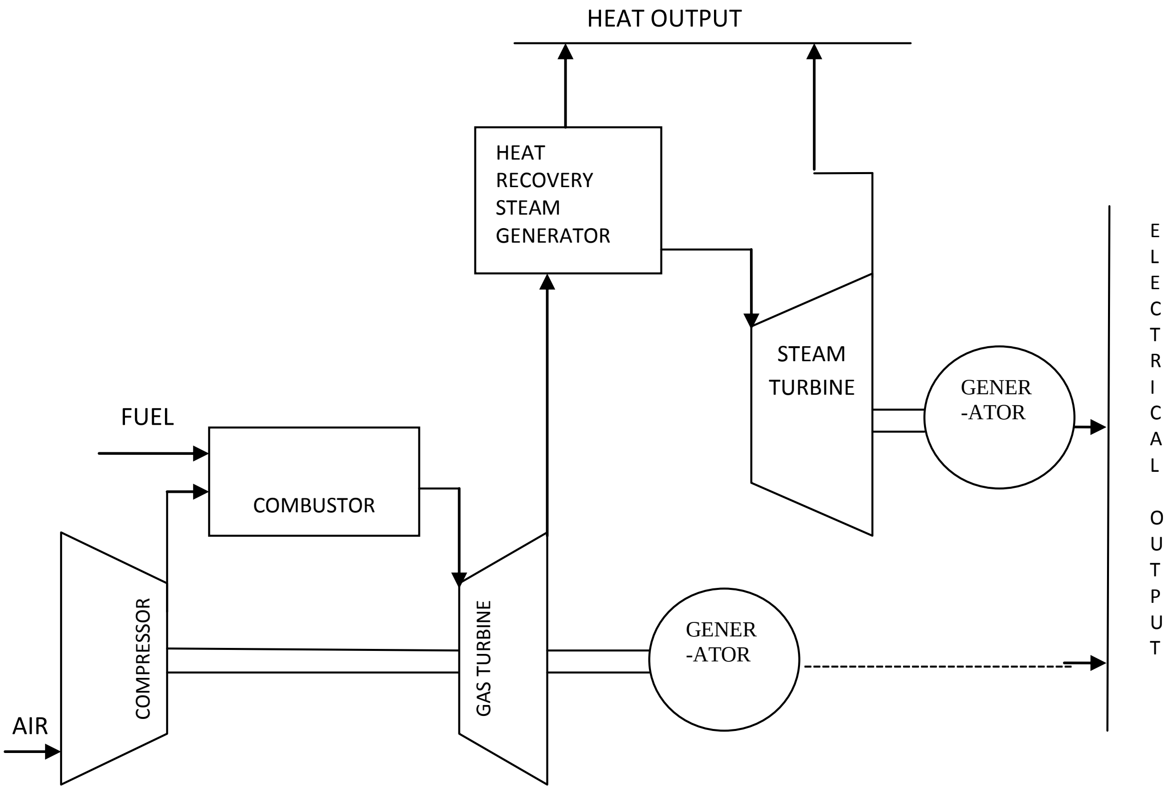

Fig2.1. Typical combined cycle CHP plant

Figure 2.1 shows a typical combined cycle CHP plant (topping cycle). The basic plant components include gas turbine/generator systems, heat recovery steam generator (HRSG) systems, and steam turbine/generator systems. The HRSG systems utilize the heat from the gas turbine exhaust to generate steam which in turn is used to operate steam turbines that drives a second electrical generator and/or is used directly in industrial, commercial or institutional applications [38]. In many plants, HRSG's are supplemented with duct firing heaters to increase the cycle efficiency (back pressure steam turbine), and ensure flexibility of operation. The plant revenue is generated from the sales of energy in both its electric (P) and thermal (H) forms. Since the fuel cost (C) is one of the major portions of plant operation, optimization of unit dispatching is achieved when dC/dP and dC/dH are minimized. In this work, practical aspects in applying such principals to combined cycle CHP plants are discussed [39].

2.2 Formulation of CHPED Problem

The problem of static dispatch determines the loads of generators in a system that will meet a power demand during a single scheduling period for the least cost. The conventional ED problem deals with only the electric power loads of the conventional thermal generators. The CHPED problem on the other hand is considerably more complicated. In this problem, both the power and process heat demands must be satisfied. The power is generated by conventional thermal generators and cogeneration units whilst the heat is generated by cogeneration units and boiler units. The complexity is further increased by the non-separable nature of the power and heat loads of cogeneration units.

The system under consideration has conventional thermal generators, cogeneration units, and heat-only units. Fig 2.2 shows the heat–power feasible operation region (FOR) of a combined cycle CHP unit. The feasible operation is enclosed by the boundary curve ABCDEF. Along the boundary curve BC, the heat capacity increases as the power generation decreases, the heat capacity declines along the curve CD. The power output of the power units and the heat output of heat units are restricted by their own upper and lower limits. The power is generated by conventional thermal generators and cogeneration units while the heat is generated by cogeneration units and heat-only units. The CHPED problem of a system is to determine the unit heat and power production, so that the system production cost is minimized, while the heat and power demands and other constraints are met [40].

The objective function of the CHPD problem, which is to be minimized, is:
Minimize

$$fcost = \sum_{i=1}^{N_p} C_i(P_i) + \sum_{j=1}^{N_b} C_j\left(P_j, H_j\right) + \sum_{k=1}^{N_h} C_k(H_k) \tag{2.1}$$

subject to the equilibrium constraints of electricity and heat production, and the capacity limits of each unit.

$$\sum_{i=1}^{N_p}(P_i) + \sum_{j=1}^{N_b}(P_j) = P_d \tag{2.2}$$

where P_i = Power generation by i^{th} Thermal power unit

P_j = Power generation by j^{th} cogeneration unit

P_d = Total power demand

N_p = Number of Thermal power units

N_b = Number of Cogeneration units

i = Index of thermal power units

j = Index of cogeneration units

k = Index of heat-only units

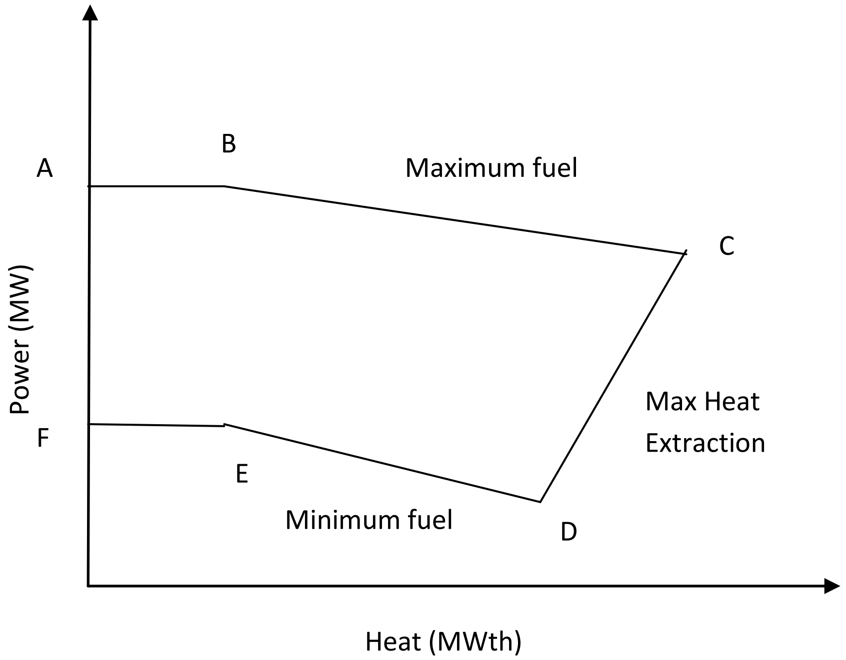

Fig 2.2. Heat-power feasible operation region for a cogeneration unit

$$\sum_{j=1}^{N_b} H_j + \sum_{k=1}^{N_h} H_k = H_d \tag{2.3}$$

where H_j = Heat generation by j^{th} cogeneration unit

H_k = Heat generation by k^{th} heat-only unit

N_b = Number of cogeneration units

N_h= Number of heat-only units

H_d = Total heat demand

$$P_i^{min} \leq P_i \leq P_i^{max}, \qquad (i = 1, \ldots\ldots, Np) \tag{2.4}$$

$$P_j^{min}(H_j) \leq P_j \leq P_j^{max}(H_j), \qquad (j = 1, \ldots\ldots\ldots, N_b) \tag{2.5}$$

$$H_j^{min}(P_j) \leq H_j \leq H_j^{max}(P_j), \qquad (j = 1, \ldots\ldots\ldots, N_b) \tag{2.6}$$

$$H_k^{min} \leq H_k \leq H_k^{max}, \qquad (k = 1, \ldots\ldots, N_h) \tag{2.7}$$

with

$$C_i(P_i) = a_i(P_i^2) + b_i(P_i) + c_i \qquad (i = 1, \ldots\ldots, Np) \tag{2.8}$$

$$C_j\left(P_j, H_j\right) = a_j\left(P_j^2\right) + b_j\left(P_j\right) + c_j + d_j\left(H_j^2\right) + e_j\left(H_j\right) + f_j\left(P_j\right)\left(H_j\right) \quad (j = 1, \ldots \ldots .., N_b) \tag{2.9}$$

$$C_k(H_k) = a_k(H_k^2) + b_k(H_k) + c_k \qquad (k = 1, \ldots \ldots, N_h) \tag{2.10}$$

where f_{cost} = total fuel cost
C_i = unit production costs of the conventional power units
C_j = unit production costs of the co-generation units
C_k = unit production costs of the heat-alone units
P_i^{min} and P_i^{max} = Lower and Upper bounds for power output of unit *i*
H_k^{min} and H_k^{max} = Lower and Upper bounds for heat production of unit *k*

The CHPED problem clearly introduces the complication of more constraints than in the required pure power ED problem. The mutual dependencies of heat and power generations from eqs. (2.5) and (2.6) introduce a complication in the integration of cogeneration units. Hence, the optimization problem of the CHPED is non-linear and highly constrained in nature.

CHAPTER 3. DIFFERENTIAL EVOLUTION

3.1 Introduction

Differential evolution is a population-based stochastic technique that minimizes (or maximize) relating to evolutionary computation, whose simple yet powerful and straight forward features make it very attractive for numerical optimization. Differential evolution uses a rather greedy and less stochastic approach to problem solving than do evolutionary algorithms. Differential evolution combines simple arithmetic operators with the classical operators of recombination, mutation and selection to evolve from a randomly generated starting population to a final solution. Differential evolution differs from conventional GA in its use of perturbing vectors, which are the difference between two randomly chosen parameter vectors, a concept borrowed from the operators of simplex optimization technique. The DE algorithm was first introduced by Storn and price [2] and was successfully applied in the optimization of some well-known nonlinear, non-differentiable, and non-convex functions.

Differential evolution is a relatively recent heuristic designed to optimize problems over continuous domains. In DE, each decision variable is represented in the chromosome by a real number. As in any other evolutionary algorithm, the initial population of DE is randomly generated, and then evaluated. After that, the selection process takes place. During the selection stage, three parents are chosen and they generate a single offspring which competes with a parent to determine who passes to the following generation. The basic idea of DE is to adapt the search during the evolutionary process. At the start of the evolution, the perturbations are large, since parent populations are far away from each other. DE generates a single offspring (instead of two as the genetic algorithm) by adding the weighted difference vector between two parents to a third parent. In respect of single-objective optimization, if the resulting vector results in a lower objective function value than a predetermined population member, then the newly generated vector replaces the vector with respect to which it was compared. In addition, the best parameter vector $F_{best,i}$ is evaluated for every generation 'i' in order to keep track of the progress that is made during the minimization process. In DE, the fittest of an offspring competes one to one with that of corresponding parent, which is different from other evolutionary algorithms. This one-to-one competition gives rise to faster convergence rate [2].

3.2 Advantages

Differential evolution algorithm has a number of significant advantages which are summarized below:

1. Differential evolution algorithm has the ability to find the true global minimum regardless of initial parameter values.
2. Differential evolution algorithm is fast and simple with regard to application [27].
3. Differential evolution algorithm requires few control parameters.
4. Differential evolution algorithm has parallel processing nature and fast convergence [41].
5. Differential evolution algorithm is capable of providing multiple solutions in a single run [42].
6. The method is effective on integer, discrete and mixed parameter optimization.
7. Differential evolution algorithm has the ability to find the optimal solution for a non-linear constrained optimization problem with penalty functions.

3.3 Theory of Differential Evolution Algorithm

For all evolutionary algorithms, the operational parameters control the balance between exploitation (using the existing material in the population to best effect) and exploration (searching for better genes). These operators frequently interact with each other, and the optimal combinations are problem-dependent, and can be difficult to find. Fortunately, evolutionary algorithms have proven to be quite robust across wide ranges of these. This section provides the solution methodology to the ED problems through DE.

3.3.1 Parameter Setup

The user must choose the key parameters that control DE, i.e. population size (L), boundary constraints of optimization variables (NG), mutation factor (f_m), crossover rate (CR), and the stopping criterion of maximum number of iterations (generations) t_{max}. The set of real power output (P_{ij}^t) of all generators is represented as the population [43]. For a system with NG generators, the population is represented as a vector of length *NG*. If there are *L* members in the population, the complete population is represented as a matrix as below:

$$Population \;=\; \begin{bmatrix} P_{11}^t & P_{12}^t & \dots\dots & P_{1\,NG}^t \\ P_{21}^t & P_{22}^t & \dots. & P_{2\,NG}^t \\ & & P_{ij}^t & \\ P_{L1}^t & P_{L2}^t & & P_{L\,NG}^t \end{bmatrix} \qquad (\, i = 1,\, 2, \dots.NG, \;\; j = 1,\, 2, \dots.L)$$

where P_{ij}^t is the i^{th} element of NG set of committed generators giving j^{th} individual of a population. In other words, it represents the real power generation of generator 'i' of the possible solution 'j'. Further, $P_{ij}^t = [P_{i1}^t, P_{i2}^t, \dots P_{iNG}^t]^T$ stands for the individual of the j^{th} individual population of real valued NG-dimensional vectors [44].

3.3.2 Initialization of an Individual Population

The initial population comprises combinations of only the candidate dispatch solutions, which satisfy all the constraints and are feasible solutions of economics dispatch. It consists of P_{ij}^t $(i = 1,2,\dots.NG, j = 1,2,\dots.L)$ trial parent individuals. The element of a parent is the combinations of power outputs of the generating units, which are chosen randomly by a random number ranging over $[P_i^{min}, P_i^{max}]$.

$$P_{ij}^t = P_{ij}^{min} + rand()(P_i^{max} - P_i^{min}) \qquad (i =1,2,..NG, j =1,2,\dots.,L) \qquad (3.1)$$

where rand ( ) is uniform random number ranging over [0,1] .

3.3.3 Evaluation

The goal is to minimize the operating cost function. Operating cost function is evaluated using the following equation:

$$C_i(P_i) = \sum_{i=1}^{NG} (a_i(P_i^2) + b_i(P_i) + c_i) \qquad (i = 1, \dots\dots, NG) \qquad (3.2)$$

3.3.4 Mutation operation (differential operation)

Mutation is an operation that adds a vector differential to a population vector of individuals according to the following equation:

$$A_{ij}^t = P_{R_1 j}^t + f_m(P_{R_2 j}^t - P_{R_3 j}^t) \qquad (i=1,2,\dots\dots.,NG , j=1,2,\dots\dots.,L) \qquad (3.3)$$

where T is the time (generation)

$P_i^t = [P_{i1}^t, P_{i2}^t, \dots\dots P_{iNG}^t]^T$ stands for the position of the j^{th} individual of a population of real valued NG-dimensional vectors.

$A_i^t = [A_{i1}^t, A_{i2}^t, \dots\dots A_{iNG}^t]^T$ stands for the position of the j^{th} individual of a mutant vector. R_1, R_2 and R_3 are mutually different integers that are also different from the running index j, f_m is the mutation factor and $f_m > 0$ is a real parameter, which controls the amplification of the difference between two individuals with indexes R_2 and R_3 (j) so as to avoid search stagnation and is usually a constant value taken from the range [0.4,1] [45].

The mutation operation using the difference between two randomly selected individuals may cause the mutual individual to escape from the search domain. If an optimized variable for the mutant individual is outside of the domain search, then this variable is replaced by its lower bound or its upper bound so that each individual can be restricted to remain within the search domain.

3.3.5 Recombination operation

Following the mutation operation, recombination is applied to the population. Recombination is employed to generate a trial vector by replacing certain parameters of the target vector by the corresponding parameters of a randomly generated donor vector. For each vector, A_i^{t+1} an index $R_5(i)$ is randomly chosen using a uniform distribution and a trial vector.

$$B_i^{t+1} = [B_{i1}^{t+1}, B_{i2}^{t+1}, \dots\dots B_{iNG}^{t+1}]^T$$

$$B_i^{t+1} = \begin{cases} A_{ij}^{t}; if(R_4(j) \leq CR) or (j = R_5(i)) \\ P_{ij}^{t}; if(R_4(j) \leq CR) or (j \neq R_5(i)) \end{cases} \quad (i = 1,2,\dots.,NG, j = 1,2,\dots..L) \qquad (3.4)$$

where $R_4(j)$ is the i^{th} evaluation of a uniform random number generation with [0,1]

CR is the crossover or recombination rate in the range [0, 1].

Usually, the performance of a DE algorithm depends on three variables: the population size, the mutation factor f_m and the CR.

3.3.6 Selection operation

Selection is the procedure whereby better offspring are produced. To decide whether the vector B_i^{t+1} should be a member of the population comprising the next generation, it is compared with the corresponding vector P_{ij}^{t}. Thus, if f denotes the cost function under minimization, then

$$P_{ij}^{t+1} = \begin{cases} B_{ij}^{t+1}, (j = 1,2,\dots..,NG);\ f(B_i^{t+1}) < f(P_i^{t}) \\ P_{ij}^{t}, (j = 1,2,\dots..,NG); \qquad otherwise \end{cases} \quad (i=1,2,\dots\dots,NG) \qquad (3.5)$$

In this case, the cost of each of trial vector B_i^{t+1} is compared with that of its parent target vector P_i^{t}. If the cost f of the target vector P_i^{t} is lower than that of the trial vector, the target is allowed to advance to the next generation. Otherwise, a trial vector replaces the target vector in the next generation [46].

3.4 Flowchart of Differential Evolution:

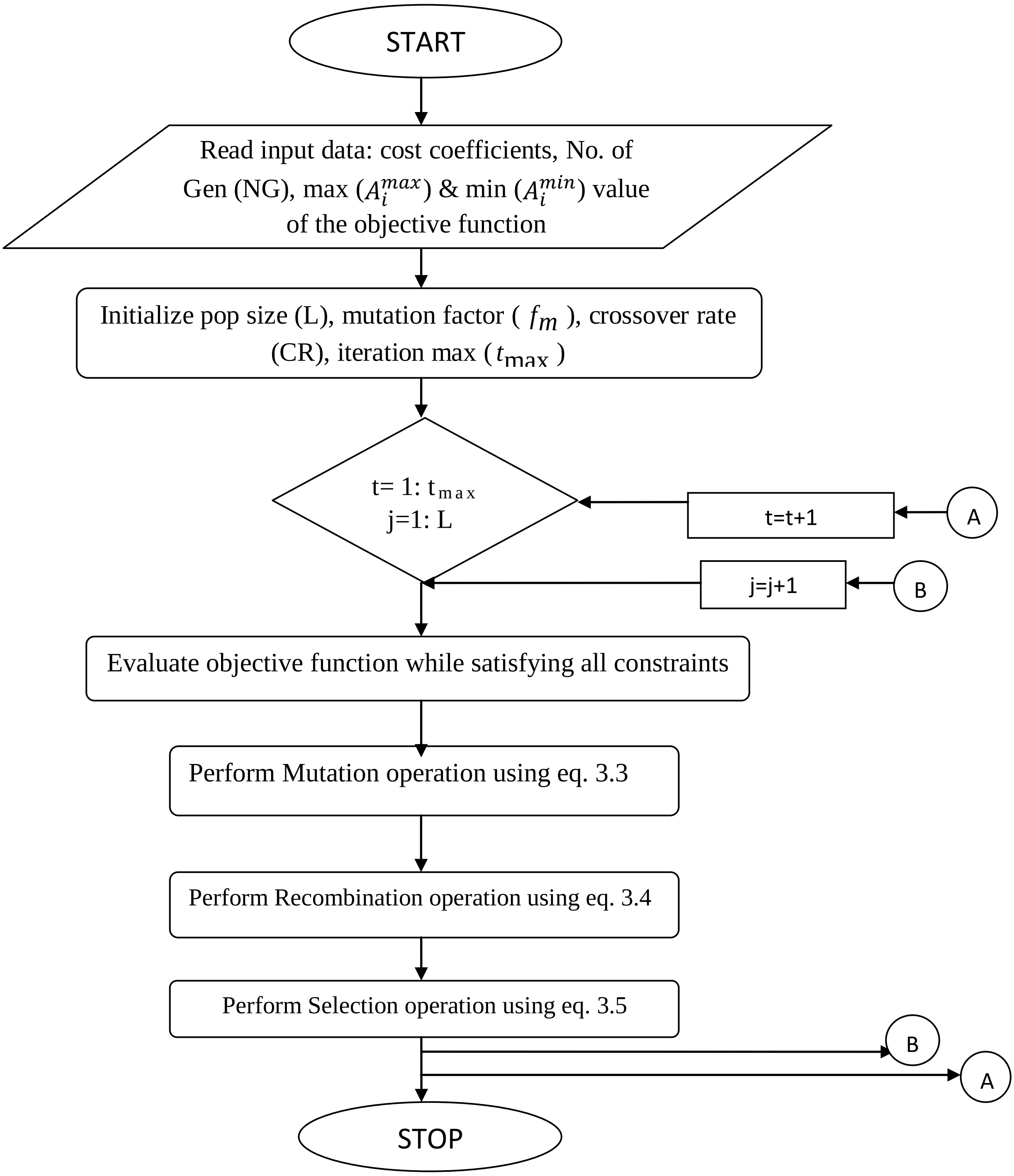

Fig. 3.1 Flow Chart of Differential Evolution technique

CHAPTER 4. COMBINED HEAT AND POWER ECONOMIC DISPATCH USING DIFFERENTIAL EVOLUTION

4.1 Problem Formulation

Combined heat and power economic dispatch determines heat and power output of generating units in a way that total production cost of the system is minimized while the power and heat demands and other constraints are satisfied. It is assumed that the system includes conventional power generating units, cogeneration units and heat-only units. In this problem, the power output of conventional and cogeneration units as well as heat production of heat-only units are the control (decision) variables which are restricted by their related upper and lower bounds. About the cogeneration units, related feasible operation regions are considered. Fig.2.2 shown in chapter 2 represents feasible operation region of a cogeneration unit. The feasible operation region is modeled by the boundary curve ABCDEF. Along the boundary curve of BC, increasing the power output leads to decreasing the heat production. While, the power output and heat production have variation with same direction during boundary curve of CD. Solution of the CHPED problem would be in this feasible region while the power and heat demands constraints are met.

The CHPED problem is formulated as an optimization problem including an objective function and its related constraints, expressed as follows:

Minimize

$$fcost = \sum_{i=1}^{N_p} C_i(P_i) + \sum_{j=1}^{N_b} C_j\left(P_j, H_j\right) + \sum_{k=1}^{N_h} C_k(H_k) \tag{4.1}$$

subject to the equilibrium constraints of electricity and heat production, and the capacity limits of each unit.

$$\sum_{i=1}^{N_p}(P_i) + \sum_{j=1}^{N_b}(P_j) = P_d \tag{4.2}$$

$$\sum_{j=1}^{N_b}(H_j) + \sum_{k=1}^{N_h}(H_k) = H_d \tag{4.3}$$

Inequality constraints:

$$P_i^{min} \leq P_i \leq P_i^{max}, \qquad (i = 1, \ldots \ldots, Np) \tag{4.4}$$

$$P_j^{min}(H_j) \leq P_j \leq P_j^{max}(H_j), \qquad (j = 1, \ldots \ldots, N_b) \tag{4.5}$$

$$H_j^{min}(P_j) \leq H_j \leq H_j^{max}(P_j), \qquad (j = 1, \ldots \ldots, N_b) \tag{4.6}$$

$$H_k^{min} \leq H_k \leq H_k^{max}, \qquad (k = 1, \ldots \ldots, N_h) \tag{4.7}$$

where P_i = Power generation by i^{th} Thermal power unit

P_j = Power generation by j^{th} cogeneration unit

H_j = Heat generation by j^{th} cogeneration unit

H_k = Heat generation by k^{th} heat-only unit

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

H_d = Total heat demand

P_d = Total power demand

It is noticeable that the complication arising in the CHPED problem is the mutual dependencies of extra constraints than in pure economic dispatch [47].

4.2 Constraints Handling

In order to satisfy the equality i.e. power balance constraint, a generator is arbitrarily selected as a dependent generator'd'. Losses are neglected. Output of dependent or slack generator is obtained as given below using equation (3.1):

$$P_d^j = P_D - \sum_{\substack{i=1 \\ i \neq d}}^{NG} P_i^j \qquad (i = 1,2, \ldots \ldots, NG), i \neq d, (j = 1,2, \ldots \ldots, L) \tag{4.8}$$

where P_D = Total power demand

If the output of the dependent generator violates its limits then this violation is corrected by fixing them either at lower or upper limits as described below:

$$P_{ij}^{t} = \begin{cases} P_i^{min}; \; P_{ij}^{t} < P_i^{min} \\ P_i^{max}; \; P_{ij}^{t} < P_i^{max} \\ P_i^{j}; \; P_i^{min} \le P_i^{j} \le P_i^{max} \end{cases} \quad (i=1,2,\ldots\ldots,NG), i \neq d, (j=1,2,\ldots\ldots,L) \tag{4.9}$$

After limiting the value of the dependent generator, a penalty term is introduced in the objective function to penalize its fitness value.

$$\text{Error 1} = \begin{cases} (P_d^{j} - P_d^{min})^2; & P_d^{j} < P_d^{min} \\ (P_d^{max} - P_d^{j})^2; & P_d^{j} > P_d^{max} \\ 0 \quad ; & P_d^{min} \le P_d^{j} \le P_d^{max} \end{cases} \tag{4.10}$$

In order to satisfy the equality constraint, a generator is arbitrarily selected as a dependent generator'd'. Losses are neglected. Output of dependent or slack generator is obtained from equation as given below:

$$H_d^{j} = H_D - \sum_{\substack{i=1 \\ i \neq d}}^{NG} H_i^{j} \qquad (i = 1,2,\ldots\ldots,NG), i \neq d, (j = 1,2,\ldots\ldots,L) \tag{4.11}$$

where H_D= Total heat demand

If the output of the dependent generator violates its limits then this violation is corrected by fixing them either at lower or upper limits as described below:

$$H_{ij}^{t} = \begin{cases} H_i^{min}; \; H_{ij}^{t} < H_i^{min} \\ H_i^{max}; \; H_{ij}^{t} < H_i^{max} \\ H_i^{j}; \; H_i^{min} \le H_i^{j} \le H_i^{max} \end{cases} \quad (i=1,2,\ldots\ldots,NG), i \neq d, (j=1,2,\ldots\ldots,L) \tag{4.12}$$

After limiting the value of the dependent generator, a penalty term is introduced in the objective function to penalize its fitness value.

$$\text{Error 2} = \begin{cases} (H_d^{j} - H_d^{min})^2; & H_d^{j} < H_d^{min} \\ (H_d^{max} - H_d^{j})^2; & H_d^{j} > H_d^{max} \\ 0 \quad ; & H_d^{min} \le H_d^{j} \le H_d^{max} \end{cases} \tag{4.13}$$

Feasible Operation region constraints

In this work, a penalizing method is proposed in which infeasible solutions are penalized in respect to their violations from feasible regions. In this method, if the output of a cogeneration unit is outside its feasible region, a penalty factor depending on the minimum distance between the cogeneration unit output and the feasible region border is employed. Fig. 4.1 shows this distance for an operating point outside the feasible region graphically.

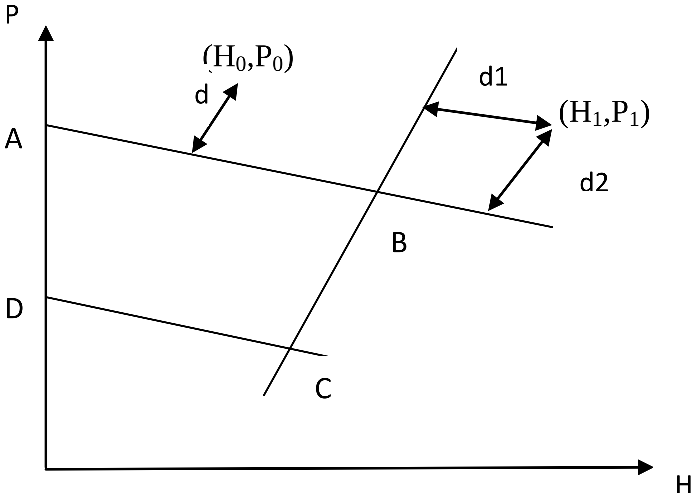

Fig. 4.1 Concept of penalty calculation for cogeneration units

If $(a(H) + b(P) + c = 0)$ is the equation of the nearest region border of the cogeneration unit (line AB in Fig.4.1), the minimum distance will be calculated using equation (4.14). Then a penalty factor is calculated using equation (4.15).

$$d = \frac{|aH_0 + bP_0 + c|}{\sqrt{a^2 + b^2}} \tag{4.14}$$

$$\text{Error 3} = \sum_{i=1}^{N_b} d_i \tag{4.15}$$

where (H_0,P_0) = output position of cogeneration unit

pf = constant value

Therefore penalty amount depends on distance directly, and more distance will result in more penalties and vice versa. Also, if the point (H_1,P_1) is in the output corner of feasible regions the infeasible solution will be penalized in respect to total distance between the point and two borders that creates the corner of feasible operation region (d1 and d2) [19].

Evaluation of Objective Function:

When penalty factors are introduced, objective function is changed to the following generalized form:

$f^j = pf \times (\text{Error 1} + \text{Error 2} + \text{Error 3}) \qquad (j=1,2,\ldots\ldots,L) \qquad (4.16)$

where f^j = fitness value of j^{th} individual

4.3 Methodology

In the CHPED problem, power output and heat production of the generating units are decision/control variables. Original DE algorithm is a simple population based evolutionary computational algorithm for global optimization. It is one of the accurate and fast meta-heuristic optimization algorithms that were introduced in 1995's by Price and Storn [2]. This section provides the solution methodology to the CHPED problems through DE.

4.3.1 Parameter setup:

The user must choose the key parameters that control the differential evolution, i.e population size (L), boundary constraints of optimization variables (NG), mutation factor (f_m), crossover rate (CR), and the stopping criterion of maximum number of iterations (generations) t_{max}. In this approach, each solution can be considered as a vector. Therefore each solution f should contain these items as follows:

Population $f = [P_{i,1},\ldots\ldots\ldots,P_{i,Np},P_{i,Np+1},\ldots\ldots,P_{i,Np+Nb}, H_{i,1},\ldots\ldots,H_{i,Nb},H_{i,Nb+1},\ldots\ldots,H_{i,Nb+Nh}]$

Further, $P_{i,j} = [P_{i,1},P_{i,2},\ldots\ldots,P_{i,Np}]$ stands for the position of the j^{th} individual of a population of real valued N_p - dimensional vectors.

4.3.2 Initialisation:

The initial population comprises combinations of only the candidate dispatch solutions, which satisfy all the constraints and are feasible solutions of economics dispatch. The element of a parent is the combinations of power outputs of the generating units, which are chosen randomly by a random number ranging over$[P_i^{min}, P_i^{max}]$.

$$P_{ij}^t = P_{ij}^{min} + rand()(P_i^{max} - P_i^{min}) \quad (i=1,2,..,NG, i\neq d, j=1,2,\ldots,L) \qquad (4.17)$$

where rand ( ) is uniform random number ranging over [0,1].

$$H_{ij}^t = H_{ij}^{min} + rand()(H_i^{max} - H_i^{min}) \quad (i=1,2,..,NG, i\neq d, j=1,2,\ldots,L) \qquad (4.18)$$

Also, the element of a parent is the combinations of heat outputs of the generating units, which are chosen randomly by a random number ranging over$[H_i^{min}, H_i^{max}]$ [48].

4.3.3 Evaluation

The goal is to minimize the operating cost function. When penalty factors are calculated, objective function i.e. cost function is evaluated using e.q. (4.16). After evaluation of objective function, a global best solution is determined $(f_{best,i}.)$

4.3.4 Mutation operation (differential operation)

Mutation is an operation that adds a vector differential to a population vector of individuals according to the following equation:

$$A_{ij}^{t} = P_{R_1 j}^{t} + f_m(P_{R_2 j}^{t} - P_{R_3 j}^{t}) \qquad (i=1,2,\ldots\ldots\ldots,NG, i \neq d, j=1,2,\ldots\ldots,L) \tag{4.19}$$

where T is the time (generation)

$P_i^t = \left[P_{i1}^t, P_{i2}^t, \ldots . P_{iNG}^t{}^T\right]$ stands for the position of the j^{th} individual of a population of real valued NG-dimensional vectors .

$A_i^t = \left[A_{i1}^t, A_{i2}^t, \ldots \ldots, A_{iNG}^t{}^T\right]$ stands for the position of the j^{th} individual of a mutant vector. R_1, R_2 and R_3 are mutually different integers that are also different from the running index i, f_m is the mutation factor and $f_m > 0$ is a real parameter, which controls the amplification of the difference between two individuals with indexes R_2 and R_3 (j) so as to avoid search stagnation and is usually a constant value taken from the range [0.4,1]

After the heat population is initialized, mutation operator creates the next population.

$$C_{ij}^{t} = H_{R_1 j}^{t} + f_m(H_{R_2 j}^{t} - H_{R_3 j}^{t}) \qquad (i=1,2,\ldots\ldots\ldots,NG, i \neq d, j=1,2,\ldots\ldots,L) \tag{4.20}$$

$H_i^t = \left[H_{i1}^t, H_{i2}^t, \ldots . H_{iNG}^t{}^T\right]$ stands for the position of the j^{th} individual of a population of real valued NG-dimensional vectors.

$C_i^t = \left[C_{i1}^t, C_{i2}^t, \ldots \ldots, C_{iNG}^t{}^T\right]$ stands for the position of the j^{th} individual of a mutant vector. R_1, R_2 and R_3 are mutually different integers [49].

4.3.5 Recombination operation

Following the mutation operation, recombination is applied to the population. Recombination is employed to generate a trial vector by replacing certain parameters of the target vector by the corresponding parameters of a randomly generated donor vector. For each vector, A_i^{t+1} and C_i^{t+1} an index $R_5\,(i)$ is randomly chosen using a uniform distribution and a trial vector $B_i^{t+1} = [B_{i1}^{t+1}, B_{i2}^{t+1}, \ldots . . B_{iNG}^{t+1}]^T$ and $D_i^{t+1} = [D_{i1}^{t+1}, D_{i2}^{t+1}, \ldots . . D_{iNG}^{t+1}]^T$ resp.

$$B_i^{t+1} = \begin{cases} A_{ij}^t; if(R_4(j) \leq CR) or (j = R_5(i)) \\ P_{ij}^t; if(R_4(j) \leq CR) or (j \neq R_5(i)) \end{cases} \qquad (i = 1,2, \ldots ., NG, i \neq d, j = 1,2, \ldots . . L)(4.21)$$

$$D_i^{t+1} = \begin{cases} C_{ij}^t; if(R_4(j) \leq CR) or (j = R_5(i)) \\ H_{ij}^t; if(R_4(j) \leq CR) or (j \neq R_5(i)) \end{cases} \quad (i = 1,2, \ldots ., NG, , i \neq d, j = 1,2, \ldots ..L) \quad (4.22)$$

where $R_4(j)$ is the j^{th} evaluation of a uniform random number generation with [0,1]

CR is the crossover or recombination rate in the range [0, 1].

Usually, the performance of a DE algorithm depends on three variables: the population size, the mutation factor f_m and the CR [50].

4.3.6 Selection operation

Selection is the procedure whereby better offspring are produced. To decide whether the vector B_i^{t+1} should be a member of the population comprising the next generation, it is compared with the corresponding vector P_{ij}^t. Thus, if f denotes the cost function under minimization, then

$$P_{ij}^{t+1} = \begin{cases} B_{ij}^{t+1}, (j = 1,2, \ldots .., NG);\ f(B_i^{t+1}) < f(P_i^t) \\ P_{ij}^t, (j = 1,2, \ldots .., NG); \qquad otherwise \end{cases} \qquad (i=1,2,\ldots ....,NG) \qquad (4.23)$$

$$H_{ij}^{t+1} = \begin{cases} D_{ij}^{t+1}, (j = 1,2, \ldots .., NG);\ f(D_i^{t+1}) < f(H_i^t) \\ H_{ij}^t, (j = 1,2, \ldots .., NG); \qquad otherwise \end{cases} \qquad (i=1,2,\ldots ....,NG) \qquad (4.24)$$

In this case, the cost of each of trial vector is compared with that of its parent target vector P_i^t and H_i^t. If the cost f of the target vector P_i^t is lower than that of the trial vector, the target is allowed to advance to the next generation. Otherwise, a trial vector replaces the target vector in the next generation [51].

4.3.7 Verification of the stopping criterion

Set the generation number for t=t+1. Repeat mutation, recombination and selection operation until the stopping criterion is met, usually a maximum number of iterations (generations),t_{max}. The stopping criterion depends on the type of problem [52].

4.4 Optimization Steps:

The CHPED problem is solved by DE algorithm. Seven steps is proposed to solve the CHPED problem as follows:

Step 1: Initializing solutions randomly.

Step 2: Penalizing infeasible solutions.

Step 3: Evaluating solutions and determining global best solution.

Step 4: Creating new solutions.

Step 5: Constraint handling and penalizing infeasible solutions.

Step 6: Evaluating solutions, selecting and determining global best solution.

Step 7: If convergence criteria satisfied exit otherwise go to step 4.

Also, Fig 4.2 shows the steps graphically [19].

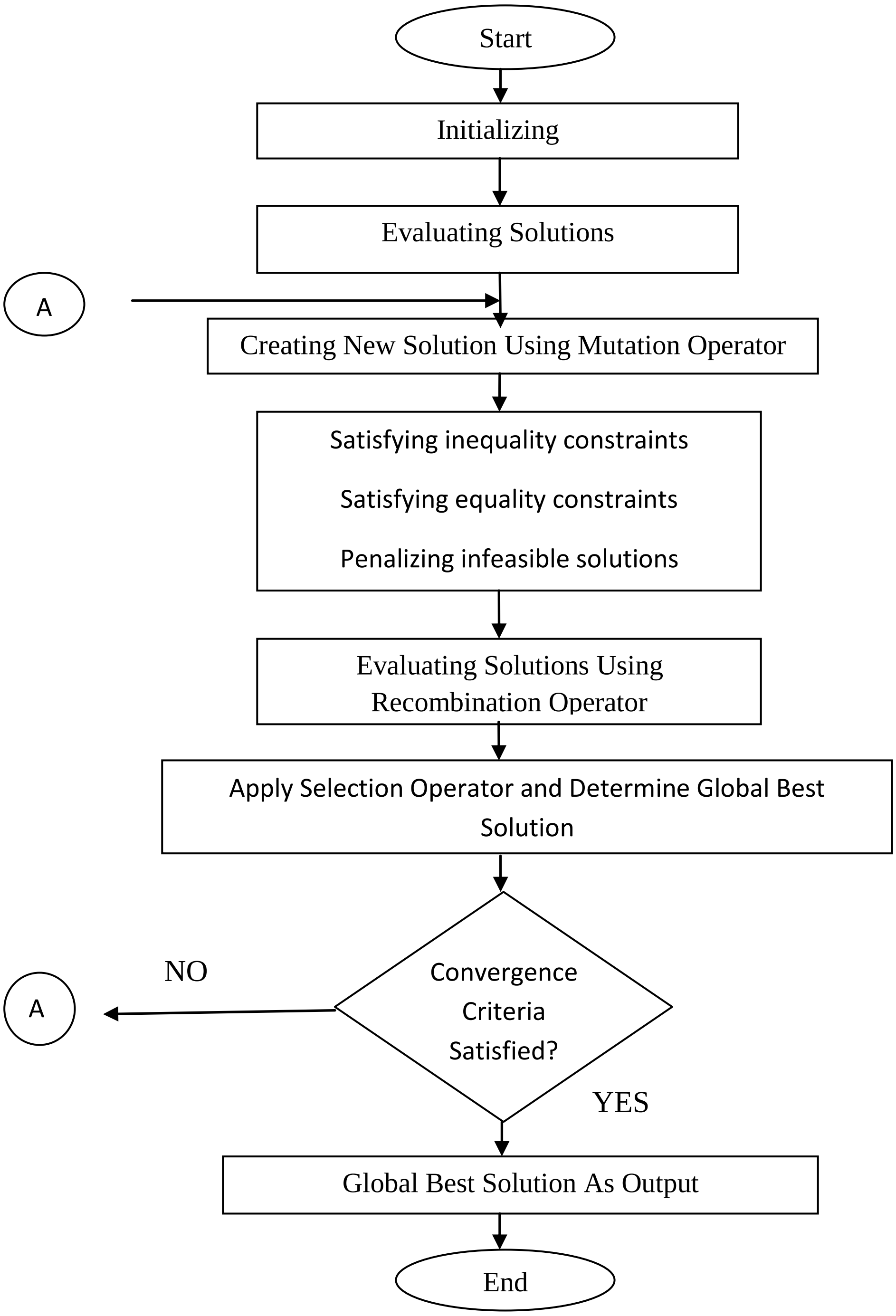

Fig.4.2. Flow Chart for solving CHPED using DE

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Introduction

The previous chapters that have been studied provide the complete knowledge of combined heat and power economic dispatch problem and its formulation using differential evolution. The algorithm of DE, which was presented in chapter 4, has been applied for solving CHPED problem. In this section, three cases are studied to illustrate the validity and effectiveness of the proposed method. The developed algorithm has been tested on three test systems [1]. Input data are APPENDIX A. The following cases have been studied- Case Study 1: For 4 generating units. Case Study 2: For 5 generating units. Case 3: For 5 generating units.

5.2 Comparison with techniques shows the effectiveness of DE technique

To show the effectiveness of DE search technique, case study I is investigated. Results are compared with genetic algorithm (GA) and genetic algorithm and tabu search (GT) method. Comparison of total operating cost is shown in table 5.1.

Table 5.1 Comparison of total operating cost for 4 units by different techniques

	P_1	P_2	H_2	P_3	H_3	H_4	Operating cost for 4 units
GA[20]	0.0	159.23	39.94	40.77	75.06	0.0	9267.2
GT[21]	0.0	157.92	26.0	42.08[a]	89.0[a]	0.0	9207.64
DE	8.47	144.24	62.14	47.28	39.17	13.68	9252

a = outside the feasible operating region of cogenerating unit 3 in (case I) having 4, generating units.

Results calculated using DE in comparison of GA and GT is found more satisfactory and all constraints are satisfied.

5.3 Case Study 1: Combined heat and power economic dispatch (CHPED) for 4 generating units.

In this case study, developed algorithm has been applied for CHPED for 4 generating units. The input parameters are taken from Table A.1. This case consists of a conventional power unit, two cogeneration units and a heat-only unit. The heat-power feasible operation regions of the cogeneration units are illustrated in fig 5.1 and 5.2.

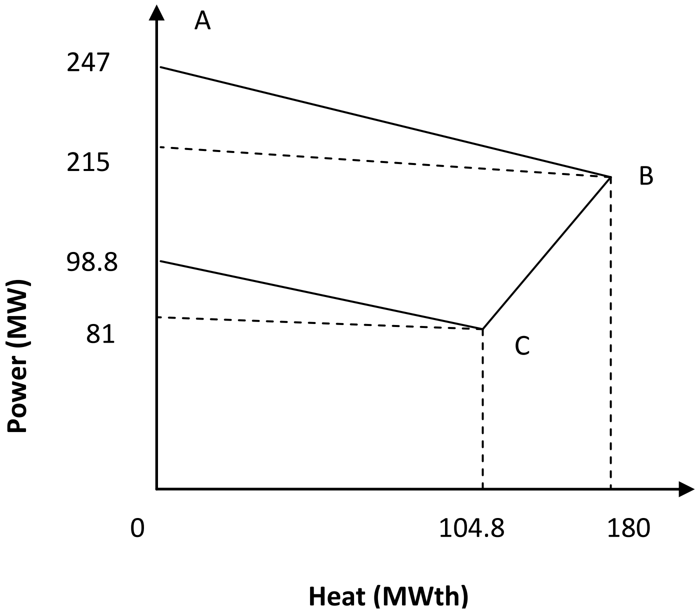

Fig.5.1. Feasible operation region for the cogeneration unit 2 (case study I) [1]

As explained in chapter-4, CHPED has been formulated with the objective of minimizing fuel cost. Feasible operation region for unit 2 has been divided into two parts in order to correct the maximum and minimum power and heat limits violation.

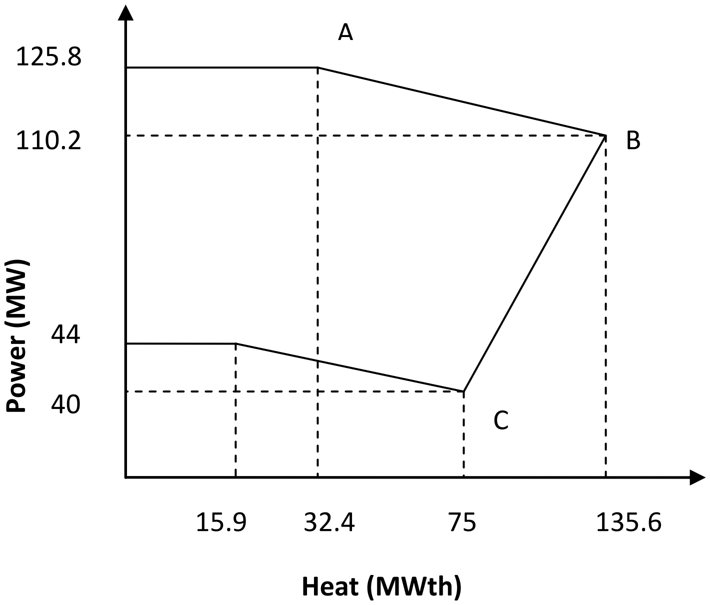

Fig.5.2 Feasible operation region for the third unit of case I and second unit of case study II [I]

Table 5.2 shows power generation (P_G), heat generation (H_G) of four-unit system problem for power demand (P_D) = 200 MW and heat demand (H_D) = 115(MWth).

Table 5.2 shows power and heat generation of 4 unit system for P_D=200 MW and H_D=115MWth

P_1(MW)	P_2(MW)	H_2(MWth)	P_3(MW)	H_3(MWth)	H_4(MWth)	Cost($)
8.47	144.24	62.14	47.28	39.17	13.68	9252

5.4 Case study II: Combined heat and power economic dispatch (CHPED) for 5 generating units.

In this case study, developed algorithm has been applied for CHPED for 5 generating units. The input parameters are taken from Table A.2. This case consists of a conventional power unit, three cogeneration units and a heat-only unit. The heat-power feasible operation regions of the cogeneration units are illustrated in fig 5.2, 5.3 and 5.4.

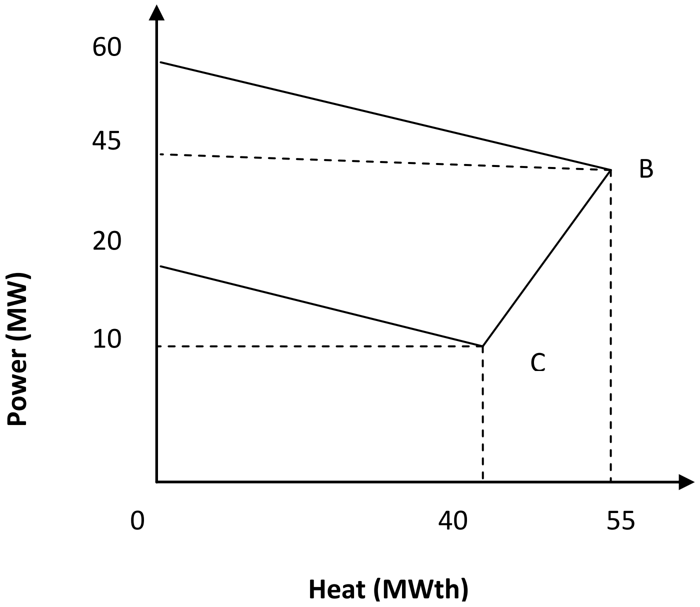

Fig.5.3. Feasible operation region for the cogeneration unit 3 of case study II [1]

Table 5.3 shows power generation (P_G), heat generation (H_G) of five-unit system problem for power demand (P_D) = 300 MW and heat demand (H_D) = 150(MWth)

Table 5.3 shows power and heat generation of 5 unit system for P_D=300MW and H_D=150MWth

P_1(MW)	P_2(MW)	H_2(MWth)	P_3(MW)	H_3(MWth)	P_4(MW)	H_4(MWth)	H_5(MWth)	Cost($)
118.13	57.95	10.84	20.36	41.53	103.55	38.83	58.79	13863

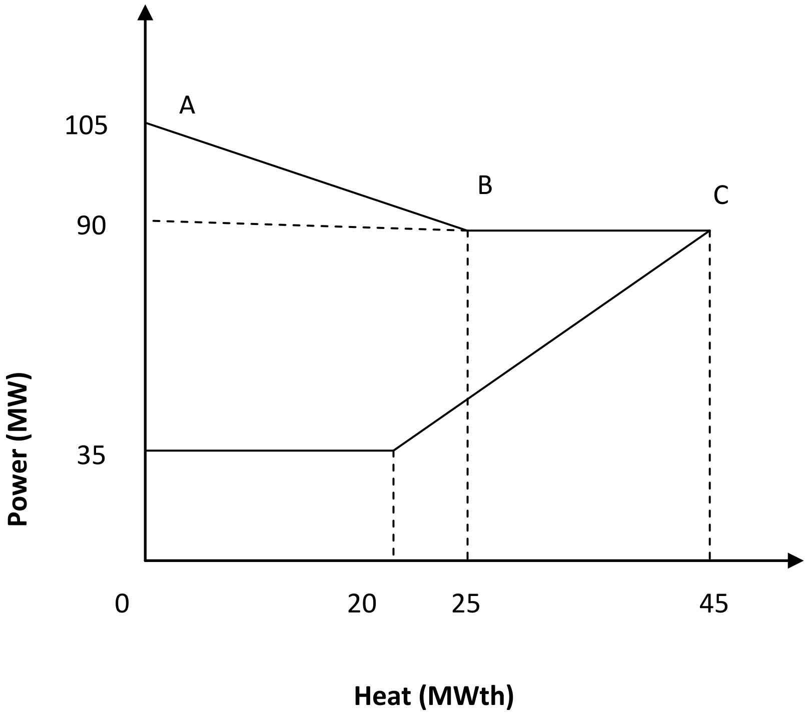

Fig.5.4. Feasible operation region for the cogeneration unit 4 of case study II [1]

5.5 Case study III: Combined heat and power economic dispatch (CHPED) for 5 generating units.

In this case study, developed algorithm has been applied for CHPED for 5 generating units. The input parameters are taken from Table A.2. This case consists of a conventional power unit, three cogeneration units and a heat-only unit. The heat-power feasible operation regions of the cogeneration units are illustrated in fig 5.2, 5.3 and 5.4.

Table 5.4 shows power generation (P_G), heat generation (H_G) of five-unit system problem for power demand (P_D) = 250 MW and heat demand (H_D) = 175 MWth

Table 5.4 shows power and heat generation of 5 unit system for P_D = 250MW and H_D=175MWth

P_1(MW)	P_2(MW)	H_2(MWth)	P_3(MW)	H_3(MWth)	P_4(MW)	H_4(MWth)	H_5(MWth)	Cost($)
123.46	65.48	82.43	14.09	28.98	46.96	21.5	42.08	12163

CHAPTER 6. CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion

The combined heat and power economic dispatch has been solved using an algorithm based on differential evolution (DE). The feasible operation region of cogeneration units are used for correcting the maximum or minimum power/heat limits violation. The CHPED problem has been solved for systems having 4 generators (having two cogenerating units) and 5 generators (having three cogenerating units) using this algorithm.

Following conclusions are drawn from the study:

1. The feasible region constraint is handled using exterior penalty factor.

2. The obtained results are found satisfactory for all the constraints.

3. The differential evolution algorithm is tested on three test systems.

6.2 Scope for future work

The scope of work after studying CHPED dispatch using DE is identified as:

1. DE algorithm can be hybridized with other random search techniques such as PSO, artificial DEE algorithm, artificial immune system algorithm, bacterial foraging optimization techniques etc.

2. CHP unit can be integrated with other source of energy such as hydrothermal plant, gas turbine unit, etc.

APPENDIX-A

Table –A.1

1. Input data for 4 generating units (for case I):

Conventional thermal unit (case I):

Unit	P_{min}	P_{max}	H_{min}	H_{max}	a_i	b_i	c_i	d_i	e_i	f_i
1	0	150	0	0	0	50	0	0	0	0

Cogeneration units (case I):

Unit	P_{min}	P_{max}	H_{min}	H_{max}	a_j	b_j	c_j	d_j	e_j	f_j
2	81	247	0	180	2650	14.5	0.0345	4.2	0.03	0.031
3	40	125.8	0	135.6	1250	36	0.0435	00.6	0.027	0.011
Feasible operating region is shown in fig 5.1 and 5.2										

Heat- Only unit (case I):

Unit	P_{min}	P_{max}	H_{min}	H_{max}	a_k	b_k	c_k	d_k	e_k	f_k
4	0	0	0	2695.2	0	0	0	23.40	0	0

Table – A.2

1. Input data for 5 generating units (for both case II and case III):

Conventional Thermal unit (Case II & III):

Unit	P_{min}	P_{max}	H_{min}	H_{max}	a_i	b_i	c_i	d_i	e_i	f_i	g_i
1	35	135	0	0	254.8863	7.6997	0.00172	0.000115	0	0	0

Cogeneration units (Case II &III):

Unit	P_{min}	P_{max}	H_{min}	H_{max}	a_j	b_j	c_j	d_j	e_j	f_j	g_j
2	40	125.8	0	135.6	1250	36	0.0435	0	0.6	0.027	0.011
3	10	60	0	55	2650	34.5	0.1035	0	2.203	0.025	0.051
4	35	105	0	45	1565	20	0.072	0	2.3	0.02	0.04
Feasible operating region is shown in fig 5.2, 5.3 and 5.4.											

Heat- Only unit (Case II &III):

Unit	P_{min}	P_{max}	H_{min}	H_{max}	a_k	b_k	c_k	d_k	e_k	f_k	g_k
5	0	0	0	60	950	0	0	0	2.0109	0.038	0

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