

Combined Heat and Power Economic Dispatch Using Civilized Swarm Optimization

A dissertation

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**Master of Engineering
In
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Submitted By:

Era Sharma

Reg. no:801241007

Under the Supervision of:

Mr. Nitin Narang

Assistant Professor



Electrical and Instrumentation Engineering Department

Thapar University, Patiala

Punjab-147004, India

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CERTIFICATE

I hereby certify that the work which is being presented in dissertation entitled, "Combined heat and power economic dispatch using civilized Swarm Optimization", in partial fulfillment of the requirements for the award of degree of Master of Engineering in Power Systems at Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Nitin Narang, Assistant Professor (EIED). The matter embodied in this dissertation has not been submitted for the award of any other degree to any other university.

Date: 15-07-2014

Era Sharma
(Era Sharma)

801241007

I certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Date: *N. Narang*
(Mr. Nitin Narang)
Assistant Professor, EIED

Countersigned by

RA
(Dr. Ravinder Agarwal)
Head of the Department
Thapar University, Patiala

S.K.M
(Dr. S.K. Mohapatra)
Sr. Professor & Dean of Academic Affairs
Thapar University, Patiala

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Era Sharma
801241007

ABSTRACT

A Civilized swarm optimization (CSO) technique, having attributes of particle swarm optimization (PSO) and society civilization algorithm (SCA) is presented in this dissertation work to solve combined heat and power economic dispatch (CHPED) problem taking into account the operational constraints of power system. CSO is a new integration based optimization technology in which the mutually interacting societies of SCA forming a civilization have been embedded in the population based self adaptive searching strategy of PSO. It is applied on CHPED problem to obtain optimum solution within feasible operating limits, satisfying the load demand at the same time. The main difficulty while dealing with a CHPED system is of multiple constraint satisfaction which is handled by following Euclidean distance approach in this work. In order to determine the efficacy of the proposed CSO based approach, it is applied on three standard test problems and the results obtained shows that the proposed CSO technique minimizes the cost at considerably smaller level of violation of constraints as compared to those obtained using other existing methods. The optimization strategy proposed in this dissertation work is easy to implement and it outperforms all the previous approaches in a respect of constraint satisfaction with cost minimization.

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1.1 Overview

Electric energy is the most versatile, easily controlled form of energy, easier to transport or distribute, convertible and flexible source of energy for our modern society. It is used to power everything varying from small devices like mobile phones to large factories which may require power in the order of 100MW and even more. In practical view, it is loss free and essentially non-polluting at the point of time of its use but at the time of its generation, it completely depends on the type of source employed for its generation or the type of generating station. With the dependence on such electrical devices, electricity demands are increasing day by day [1]. An essential strategy to meet these hiking demands for electric energy, two prolonged approaches should be followed:

1. Firstly, the available electric energy should be utilized in a more efficient and economical way.
2. Secondly, production of energy should be in most economical and least damaging manner.

In a view to first approach mentioned above, cogeneration sets are significantly operated now a day. Cogeneration sets are basically power generating systems having output as both heat and power. Therefore, the heat as the primary output form is used to solve two purposes i.e. produce secondary output that is power without any extra involvement of heat input and serving as heat energy for deriving other devices in power system [2]. But the main problem with combined heat and power type of system is its dependence of power and heat on one another. Also, feasible operation region is responsible for limiting the area of its working. Thus, combined heat and power economic dispatch (CHPED) is a complex problem and should be handled carefully. It involves the proper scheduling of heat and power for various separately working generating units and cogeneration sets with the satisfaction of all equality and inequality constraints [3]. Equality constraints involved are demand fulfillment for both heat and power while inequality constraints deals with feasible operating region and can be solved by laying the operating points within the region of its operation.

Above illustrated second approach involves optimization strategy. It deals with minimizing the overall cost of generation of electric energy [4]. For the optimization of a particular problem, the cost must be minimized such a way that all the constraints to the problem must be satisfied in a well defined manner so as to lay the overall solution within the operational limits of generating units. There are many optimization techniques implemented so far which includes deterministic approaches like linear programming approach, lagrangian relaxation method, dynamic programming etc. and others are stochastic searches including genetic algorithm (GA) [5-8], evolutionary programming (EP) approach [9], particle swarm optimization (PSO) [10-20], civilized swarm optimization (CSO) [21,22], society civilization algorithm (SCA) [23], differential evolution (DE) [24-26], harmony searching algorithm [27] etc. Some of these strategies suffer with the disadvantage of early trapping into local minima and some of these does not lead to global results because of large step size. Some of these involve differential equation for their solution but such type of techniques lead to complex problem and thus, difficulty in obtaining good results.

1.2 Review of Literature

Initially techniques used for obtaining the solution of CHPED problem were deterministic i.e. the direction of search is not known and the input regarding this criterion is not available at each step. P. S. Nagendra Rao [1] encountered with cogeneration units having quadratic cost functions and presented a solution for the CHPED problem. But this approach depends entirely on step size and may derive the whole system into oscillations with inappropriate choice [2]. Thus, non-linear optimization algorithm was then employed to eliminate above discussed problems. A. M. Jubril et al. [2] presented the semi-definite programming approach to obtain solution for the CHPED problem. Cong Liu et al. [3] carried out the economic load dispatching of combined-cycle gas turbine generating units using mixed-integer programming and lagrangian relaxation method was employed with monotonically increasing cost function. A. Sashirekha et al. [4] presented two level algorithm to solve the CHPED problem. However, these methods were not able to optimize discontinuous or non-monotonic input /output models [10].

Alternative to the above discussed methods, stochastic approaches having inbuilt feature for considering uncertainty factors were employed. Such heuristic techniques provide

a well balance between exploration and exploitation. Genetic algorithm is a simple and flexible approach due to its ability to explore satisfying solution with proper constraint satisfaction. Diverse combinations of functions of crossover and mutation in GA have been investigated. P. Subbaraj et al. [5] solved the CHPED problem by implementing a self adaptive real-valued coded GA (RCGA). M. Basu [6] presented sorting genetic algorithm-II which is basically non-dominated for solving CHPED problem formulated with the nonlinear and constrained features considered as a multi-objective optimization problem. Nidul Sinha et al. [7] solved CHPED problem using GA technique. Ching-Tzong Su et al. [8] presented the solution of CHPED problem by an improved GA approach using the concept of multiplier updating. Main disadvantage with GA is the increase in iteration time with increase in number of units. Evolutionary programming proves to be an effective technique in obtaining the solution for non-linear economic dispatch problems without having any restriction on size of the problem or shape of the cost curve [10]. Kit Po Wong et al. [9] developed an EP based algorithm for the CHPED for cogeneration systems.

Differential evolution method requires very few parameters to be set. M. Basu [24] presented DE method for solving the CHPED. Arsalan Najafi et al. [25] solved CHPED using an improved DE approach. Nidul Sinha et al. [26] investigated the performance of DE for solving CHPED problems in power systems. But local trapping in DE is frequent due to its intrinsic differential property [10]. A random behavioral searching strategy has the advantage of avoidance of premature convergence and discovery of good solutions. It may include Harmony search algorithm, colonial algorithm, artificial bee colony algorithm, firefly algorithm etc. A. Vasebi et al. [27] solved the CHPED problem using a harmony search technique. However, the solution obtained from these techniques operates with slower convergence rate.

All the above discussed methods were efficient only for problems with low dimensionality. While dealing with systems having larger number of generating units, each technique results in its own particular disadvantage until hybrid meta-heuristic techniques came into picture which involves integration of two strategies and fulfils the shortcomings of one another [10]. Hybridization can be between two stochastic techniques or local searching and random searching algorithms or between two stochastic techniques. Vo Ngozc Dieu et al. [28] proposed an augmented lagrange-hopfield network to solve CHPED problem. Provas

Kumar Roy et al. [29] presented a teaching learning based optimization for solution of CHPED with bounded feasible operating region. It resulted in better results with less computational time.

Particle swarm optimization has faster rate of convergence, thus, yielding satisfactory results still it get trapped into local minima and does not converge the problem optimally and searching process reaches the local search region and thus not able to exploit best solution. Therefore, it has the limitation of less exploration as global searching ability [10]. Yamille del Valle et al. [10] presented an elaborated survey of the basic structure of PSO and its diverse form of variants. Gary G. Yen et al. [12] suggested a technique for exchanging information between various swarms in PSO. Sabine Helwig et al. [13] proposed and compared various bound handling techniques for PSO. Jun Sun et al. [14] introduced mainstream to investigate the searching capability of a particle using quantum behaved PSO algorithm and its novel parameter based control method. Chukiat Worasuchep et al. [15] proposed RCGA consisting of hybrid of PSO and generation gap model using parent centric recombination operator. PSO is implemented to various problems in power system. V. Ramesh et al. [16] presented an improved PSO algorithm with a selection operator to solve CHPED problem. F. van den Bergh et al. [17] investigated trajectories of particles to include the effect of the inertia term and leading to the conclusion that each particle ultimately converges to a stable operating point. H.A. Behnam Mohammadi-Ivatl et al. [18] solved CHPED problem implementing a novel time varying acceleration coefficients PSO (TVAC-PSO) approach. Gunjan Tyagi et al. [19] solved CHPED problem using TVAC-PSO. Shayanfar et al. [20] presented a PSO with improved inertia weight factor for solving CHPED problem.

Tapabrata Ray et al. [23] suggested society civilization algorithm (SCA) making use of the intra and intersociety interactions to solve constrained optimization problems. A. Immanuel Selvakumar et al. [21] presented civilized swarm optimization (CSO) by integrating SCA and PSO. Its efficiency was tested for a set of multi-minima economic load dispatch problems and superior results were obtained. A. Immanuel Selvakumar [22] obtained the solution for multi-objective short-term hydrothermal scheduling using CSO algorithm. In this thesis work, a new emerging hybrid technique, CSO [21, 22] have been introduced which is an integration of SCA and PSO. This approach provides a well balance

between exploration using PSO responsible entirely for the local searching operation and exploitation using SCA using which global search is carried out. Thus, CSO technique is applied on both ELD problem and hydrothermal scheduling. But it has never been implemented on CHPED problem so far.

1.3 Objective of the Work

Civilized swarm optimization technique is implemented on combined heat and power to obtain economic load dispatch and global solution of the problem is thus obtained assuring constraint satisfaction. Civilized swarm optimization algorithm is basically a hybridized structure constituting PSO and SCA in which PSO approach helps in exploring a local search area for optimal solution and SCA leads to exploitation of the explored area for better results. In this research work, inequality constraints for cogeneration units are considered and handled using Euclidean distance approach. Proposed technique yield satisfying results and prove to be better as compared to other optimization methods.

1.4 Organization of Dissertation

The proposed thesis work titled as “Combined heat and power economic dispatch using civilized swarm optimization” has been summarized in six chapters. Chapter one provides a detailed introduction, brief literature review pertaining to problem and objective of the work. Chapter two explores the structure of CSO, its algorithm, fundamental aspects building it and their comparison terminology. Chapter three highlights the formulation of CHPED. Chapter four highlights the solution methodology for CHPED problem using civilized swarm algorithm. Chapter five covers the results concluded from various test systems. Chapter six concluded the dissertation work and summarizes the scope for future work followed by reference section.

2.1 Introduction

Civilized swarm optimization is a hybridized embedded structure comprising of PSO and SCA where the swarm of PSO is considered to be the civilization in case of SCA. Qualities of both PSO and SCA are included in CSO which equally balances the exploration of new promising areas and exploiting these areas to obtain global minimum [22]. Particle swarm optimization involves the modification of the position of particles based on their personal best experience and that of swarm while superiors are followed by rest of civilization in case of SCA. It thus fulfils the essential demands of a meta-heuristic algorithm in which more superior solutions are followed by less superior solutions [22]. Thus hybridization of two evolutionary techniques results in an efficient and satisfactory integrated technology which can be easily implemented to any practical optimization problem. Civilized swarm optimization is a powerful hybrid technique combining advantages of both SCA and PSO. Following are a few points of comparison between them:

- Society civilization algorithm provides a well balance between local searching strategy and global search [23]. It facilitates the exploration of promising area effectively and exploitation of these searched areas efficiently in a well balanced manner while PSO have the capability of utilizing the personal experiences of the particles efficiently.
- In PSO, the gathered information regarding the search space is used successfully in deciding the optimal searching area whereas SCA fails to do so [23].
- Civilized swarm optimization possesses a detailed knowledge of the searching space because of the integration of strengths of both SCA and PSO strategies [21].
- It provides a faster convergence rate and enhanced quality of results with proper satisfaction of constraints [22].
- Particle swarm optimization in comparison to SCA has the individuals obtaining the global best value considering their own experiences as well. This utilization of the personal experiences makes them to exploit a promising region by moving inside formed societies [22].

It is clear from the above discussion that CSO is a hybrid technique comprising of SCA and PSO. Therefore, it can be concluded that SCA and PSO are two important aspects of CSO to be understood in order to simplify the performance analysis of CSO approach. These are explained as follows:

2.1.1 Society Civilization Algorithm

Meta-heuristic methods using socio-behavioral models prove to be good result yielding strategies that are based on the fact that living beings evolve at a much faster rate by following cultural evolution. Society civilization algorithm being introduced by Ray and Liew [24] finds global solutions based on intra and inter communicating mechanism [23]. A society indicates a cluster of individuals in the search space performing well which help other belonging individuals in the pre-defined society to improve through interactions among them and a civilization constitutes summation of thus formed societies at a defined point of time [21]. Such an exchange of information results in the updating of a point towards a better performing such as society leaders belonging to a particular society makes them to migrate from one particular society to another. This procedure of society leader migration improves the local searching ability, corresponds to search optimally promising regions in the parametric area [22] and drags the average performing societies towards the better-performing ones, thus leading to turn the focus of search to optimal regions in the parametric space. The SCA implemented for CHPED problem is explained as follows [23]:

Step1 Initialization of civilization

A set of all decision variables in the search space is referred to as the individual of the civilization. Civilization consisting of all the individuals is created through random initialization within the maximum and minimum limits and is represented as a vector of length N as indicated in Eq. (2.1) if there are N decision variables.

$$X_j = [X_{1j}, X_{2j}, \dots, X_{ij}] \quad (i=1, \dots, M; j=1, \dots, N) \quad (2.1)$$

Such that

$$X_{ij}^{\min} \leq X_{ij} \leq X_{ij}^{\max}$$

where X_{ij} is the individual with i decision variable for the solution j.

Then the civilization with number of individuals as M is represented as a matrix at it^{th} iteration as indicated in Eq. (2.2).

$$Civ(it) = [X_1, X_2, \dots, X_j, \dots, X_M] \quad (2.2)$$

where ‘it’ indicates the number of iteration.

Step2 Society leaders’ selection

The individuals of the civilization are separated at every point of time into a number of mutually exclusive clusters called societies based on their Euclidean distance [24] which basically specify the shortest distance among the individuals and a collection of all such societies refers to the civilization. The individuals of civilization are arranged in ascending order based on obtained objective function values and the first N_s individuals (N_s indicating the number of societies) are identified as society leaders which can be represented as:

$$SL(it) = [SL_1, SL_2, \dots, SL_{N_s}] \quad (2.3)$$

Step3 Civilization leader selection

Civilization leader is basically the society leader with minimum objective function value (OF) and it should belong to the set of society leaders. For the first iteration, civilization leader is directly included to the forming swarm while for the proceeded iterations,

$$OF(CL(it + 1)) = \begin{cases} OF(CL(it + 1)) & ; OF(CL(it)) > OF(CL(it + 1)) \\ OF(CL(it)) & ; OF(CL(it)) \leq OF(CL(it + 1)) \end{cases} \quad (2.4)$$

Step4 Society members’ selection

The remaining individuals of the civilization after the civilization leader and society leaders are evaluated at a particular point of time forms the society members and collection of all such society members in the civilization is thus represented as SM (it). A set of society members N_R is thus formed by remaining individuals, i.e. $N_R = M - N_s$

$$SM(it) = [SM_1, SM_2, \dots, SM_{N_R}] \quad (2.5)$$

Here $SM(it)$ belongs to $Civ(it)$ such that there exist no common element between any society member and society leader.

Step5 Society formation

The Euclidean distance (D_s) among the society members and the society leaders are determined based for each SM_r belongs to $SM(it)$ and based on this distance it is decided to which society it is going to be attached as follows:

$$D_s = \sum_{i=1}^N (SM_{ir}(it) - SL_{ik}(it))^2 \quad (k = 1, 2, \dots, N_s; r = 1, 2, \dots, N_r) \quad (2.6)$$

Step6 Forming new civilization

For the next generation, the civilization is considered as an empty set and the civilization leader is directly included into the new civilization for next iteration. All society leaders $SL_k(t)$ are made to follow civilization leader and are included into the new civilization as below:

$$X_k^{SL}(it+1) = CL_k(it) + N(0, \sigma) \times \sum_{i=1}^N (CL_i(it) - SL_{ik}(it))^2 \quad (k = 1, 2, \dots, N_s) \quad (2.7)$$

All society members, $SM_r(t)$ are updated based on their respective society leaders and added to the new civilization:

$$X_r^{SM}(it+1) = SL_k(it) + N(0, \sigma) \times \sum_{i=1}^N (SL_{ik}(it) - SM_{ir}(it))^2 \quad (k=1, 2, \dots, N_s; r=1, 2, \dots, N_r) \quad (2.8)$$

where k indicates the society to which SM_r is attached and $N(0, \sigma)$ denote a normalized random initialization between the values 0 to variance of normal distribution (σ).

Step7 Terminating step

Whenever iteration number becomes greater than maximum count of iteration i.e. $\{it = IT^{\max}\}$, then operating optimization process is terminated, otherwise, go to step 2 and repeat the whole process with increase in iteration number in every go.

2.1.2 Particle Swarm Optimization

Particle swarm optimization is basically a self-adaptive, food searching strategy introduced by Kennedy and Eberhart [11] in 1995 and successfully implemented on various optimization problems. Stochastic optimization techniques provide an effective method to deal with complicated power system optimization problems [12]. Particle swarm optimization method represents social behavior of individuals such as flocking of birds and fish schooling [13]. In this algorithm, various particles fly in given area called search space and the direction of a particle is defined using global best value and personal best experience. Most of the optimization problems in power system have complicated structured nonlinear features having constraints which are difficult to handle. It is proved to be very effective approach in obtaining solution for a number of complex optimization problems [14]. The PSO algorithm uses a swarm consisting of a number of particles that moves around a pre-specified search space looking for the economically best solution [15]. Each particle in the swarm gather information and keeps a track regarding its position in the pre-defined area. Particle swarm optimization searches in parallel using a group of particles which means no individual of the swarm gets eliminated. It is a kind of searching strategy that traces the motion of a birds flocking [16]. The velocities of all the particles belonging to the swarm are modified at every iteration and updated using following equation:

$$V_{ij}(it+1) = w \times V_{ij}(it) + C_1 \times \text{rand}_1() \times (P_{ij}^{\text{best}} - P_{ij}) + C_2 \times \text{rand}_2() \times (G_i^{\text{best}} - P_{ij}) \quad (2.9)$$

The particles position are also modified at each step and updated between successive iteration based on the following equation [17]:

$$P_{ij}(it+1) = P_{ij}(it) + V_{ij}(it+1) \quad (j = 1, 2, \dots, M; i = 1, 2, \dots, N) \quad (2.10)$$

where C_1 and C_2 are acceleration coefficients; $V_{ij}(it)$ is velocity of each particle; $V_{ij}(it+1)$ is modified velocity of each particle; $\text{rand}_1()$ and $\text{rand}_2()$ are the random numbers uniformly distributed in the interval [0,1]; w is the inertia weight whose value decreases as the number of iterations increases and is given by the following expression [18]:

$$w = w^{\text{max}} \times \frac{w^{\text{max}} - w^{\text{min}}}{IT^{\text{max}}} \times it \quad (2.11)$$

where w^{max} initial weight; IT^{max} maximum iteration number and w^{min} final weight.

The limit for velocity must be assumed in a way so that the particle is made to acquire improved position in every go towards the target. If its selected value is very high, chances are that particles fly off and good solutions may not be achieved. If its selected value is very small, it may result in the incapability of the particles to explore well. The standard value is around 10-20% of its dynamic value [19].

2.2 Civilized Swarm Optimization

Civilized swarm optimization is a hybrid structure of PSO and SCA which is used as the optimizer to solve various engineering design problems. It involves the interactions between various individuals of the swarm enhancing the probability of obtaining good results, improves the global searching ability and results in better performing individuals over time which leads to globally promising region exploration. These individuals are grouped in different societies based on their relative coordination. All such societies are assigned with a society leader each which is being followed by the society members [23]. Out of all the society leaders, the best performing individual is considered to be the civilization leader. All society leaders are made to modify themselves according to the civilization leader. The collection of all the societies formed in search space constitutes the civilization. The society members compete among themselves with respect to the society leader and society leader with respect to the civilization leader [21]. The best performer out of all the individuals ultimately forms the global best solution. Random initialization of all the individuals in the swarm and their velocities are carried out in such a manner so as to fall within the pre-specified limits as explained in PSO. Process of identification of society leaders (SL) and society members (SM) is similar in SCA. For each society member, the distance between each of the society member and leaders is calculated using Eq. (2.8). Based on the minimum Euclidean distance, particular society member is attached to that society leader in its own society. Society leader with minimum objective function value is considered to be the civilization leader of the swarm for a particular iteration.

The updating for velocity of different sections of the swarm i.e. civilization leader, society leader and society member is done based on step by step process. The new velocity for civilization leader is calculated as below:

$$V_{iL}(it+1) = w \times V_{iL}(it) + C_L \times \text{rand}_1() \times (P_{iL}^{\text{best}}(t) - L_i(it)) \quad (i = 1, 2, \dots, N) \quad (2.12)$$

As the society leaders are made to follow the civilization leader, the updated velocity for society leaders are given below:

$$V_{ik}(it+1) = w \times V_{ik}(it) + C_{SL_i} \times rand_2() \times (P_{ik}^{best}(it) - SL_{ik}(it)) + C_{SL_2} \times rand_3() \times (L_i(it) - SL_{ik}(it))$$

($k = 1, 2, \dots, N_s$; $i = 1, 2, \dots, N$) (2.13)

The society leaders are followed by the society members, the new velocity for society members can be calculated as below:

$$V_{ir}(it+1) = w \times V_{ir}(it) + C_{SM_i} \times rand_4() \times (P_{ir}^{best}(it) - SM_{ir}(it)) + C_{SM_2} \times rand_5() \times (SL_{is}(it) - SM_{ir}(it))$$

($i = 1, 2, \dots, N$, $r = 1, 2, \dots, N_R$; $k = 1, 2, \dots, N_s$) (2.14)

where $rand_1()$, $rand_2()$, $rand_3()$, $rand_4()$ and $rand_5()$ are uniformly distributed random numbers belonging to the interval [0,1], C_L Coefficient is responsible for deriving the SL to its self best position; C_{SL_i} derives SL towards its self best position; C_{SL_1} derive SL towards CL; C_{SM_i} accelerates SM towards its self best position; C_{SM_1} Coefficient which derive SM towards its SL.

The position P_{best} for each of the individuals of swarm can be updated using Eq. (2.12), (2.13) and (2.14) respectively. For the next iteration, the swarm is initialized as an empty set and the CL is included to the initialized swarm by moving it to a new position in it and can be represented as:

$$X_L(it+1) = CL(it) + V_L(it+1) \quad (2.15)$$

The society leaders and the society members, identified before at previous iteration are also included to the new swarm by moving it to a new position as given below:

$$X_{SLK}(it+1) = SL_K(it) + V_{SLK}(it+1) \quad (2.16)$$

$$X_{SMI}(it+1) = SM_{SMI}(it) + V_{SMI}(it+1) \quad (2.17)$$

3.1 Combined Heat and Power Generation

Conventional methods of generating electricity are highly inefficient as heat energy is totally wasted in this process [25]. The principle of a combined heat and power generation also called cogeneration is to recover heat and power both from a single fuel which results in increase in the overall efficiency for such a conversion. Thus, combined heat and power generation may be defined as the generation of energy in different forms resulting from single fuel source such as coal, radioactive substance etc and can be utilized effectively for other purposes. Furthermore, the generated heat acts as the by-product and is available for its use without further involvement of any primary fuel [24]. Ordinarily, the primarily generated energy form is thermal (steam) which is further use to produce the secondary form i.e. power [26]. Thus it is clear from the above discussion that for a wide scale of power system generation, cogeneration system proves to be more advantageous than conventional systems of generation. Such a system of generation is a modern approach and suitable to adapt for simultaneous entity generation [27]. It is an interesting technology in industrial sector, particularly in the oil or gas field, for increasing utilization of energy and emission reduction for offering electrical power, reduction in environmental hazards and economical benefits thus, improving power reliability, conservation of sources like fossil fuels, for instance say coal or any radioactive substance and leading to efficiency hike in fuel conversion process [16]. It serves the following benefits:

- Reduced emissions of greenhouse gases to the environment.
- Waste disposal problem is solved since these substances serve as fuels for cogeneration schemes like biomass fuels and waste materials such as agricultural waste and thus are economical in nature [4].
- Increased efficiency due to effective utilization of fossil fuels during energy conversion process [19].
- Industrial and commercial users are provided with surplus amount of energy while offering heat at affordable prices to domestic users leads to large savings in cost [23].

3.2 Combined Heat and Power Economic Dispatch

Overall cost minimization is very necessary due to present condition of the energy crisis in the world and rapid hike in prices with large interconnection of the electric networks. Thus, any saving on the part of the operating procedure of the power system will definitely bring a significant reduction in the quantity of fuel consumed thereby reducing the overall operating cost as well. The main motive of energy supplying entities is to provide reliable power supply to its consumers with good quality at economical cost.

In modern electrical power system, there are various types of optimization problems such as ELD, CHPED, optimal power flow, generation and transmission planning, forecasting & control and unit commitment [26]. Economic load dispatch is one such major optimization issue in power system. It deals with economically allocating the electric power to different generating units for the purpose of reduction in total cost while satisfying the constraints imposed on the generating units and other environmental considerations for power only. On the other hand, the purpose of carrying out dispatching of the combined heat and power is to determine the best operating point for power and heat generating units in an economical manner in such a way that demands for both heat and power are fulfilled while each generating unit is made to operate within a specified boundary. Thus, the scheduling involves those operating points of power and heat operation which should satisfy demands and should lie within the specified boundary of feasible operation region in which heat is a function of power and power is a function of heat [28]. Thus, any change in the setting of one parameter may result in instability of other parameter.

3.3 Problem Formulation of CHPED

In CHPED problem, scheduling of the various units is required to fulfill the heat and power demand simultaneously in the most economical way. This CHPED problem is formulated with quadratic nature of objective function and linear constraints of both heat and power.

3.3.1 Cost function

The problem includes conventional heat and power units and cogeneration units. The cost function corresponding to each of the operating unit individually can be obtained by

multiplying input-output curve with fuel cost burned in that unit [27] and can be represented as the summation of cost functions for all the units separately as given below:

$$C_c(H_c) = \alpha_c + \beta_c H_c + \gamma_c H_c^2 \quad (3.1)$$

$$C_e(P_e) = \alpha_e + \beta_e P_e + \gamma_e P_e^2 \quad (3.2)$$

$$C_{chp}(P_{chp}, H_{chp}) = \alpha_{chp} + \beta_{chp} P_{chp} + \lambda_{chp} P_{chp}^2 + \delta_{chp} H_{chp} + \psi_{chp} H_{chp}^2 + \xi_{chp} P_{chp} H_{chp} \quad (3.3)$$

$$F(X) = \sum_{e=1}^E C_e(P_e) + \sum_{chp=1}^{CHP} C_{chp}(P_{chp}, H_{chp}) + \sum_{c=1}^C C_c(H_c) \quad (3.4)$$

where c, e, chp indicate the indices of conventional power units, heat units and combined heat and power units respectively and C, E, CHP represent the total number of conventional power units, conventional heat units and combined heat and power units.

3.3.2 Equality constraints

For power and heat balance, equality constraints must be satisfied as indicated in Eq. (3.5) and (3.6). The equality constraints represent the basic load flow equations i.e. total generation of electric energy should be equal to total requirement by the consumers indicating the demand plus total line loss. Both heat and real power balancing is required throughout the scheduling process in the problem [15]. Power and heat balance equations for power unit, heat unit and cogeneration unit are shown:

$$\sum_{e=1}^E P_e + \sum_{chp=1}^{CHP} P_{chp} = P_D + P_L \quad (3.5)$$

$$\sum_{c=1}^C H_c + \sum_{chp=1}^{CHP} H_{chp} = H_D \quad (3.6)$$

3.3.3 Inequality constraints

Inequality constraint indicates minimum and maximum limits for operation of all the units independently which is totally based on their output values [17]. This generation should lie within the operating limits of the respective units for their proper operation. Capacity limits for conventional power and heat only units and cogeneration unit are:

$$P_e^{\min} \leq P_e \leq P_e^{\max} \quad (3.7)$$

$$H_c^{\min} \leq H_c \leq H_c^{\max} \quad (3.8)$$

$$H_{\text{chp}}^{\min}(P_{\text{chp}}) \leq H_{\text{chp}} \leq H_{\text{chp}}^{\max}(P_{\text{chp}}) \quad (3.9)$$

$$P_{\text{chp}}^{\min}(H_{\text{chp}}) \leq P_{\text{chp}} \leq P_{\text{chp}}^{\max}(H_{\text{chp}}) \quad (3.10)$$

3.3.4 Active power transmission line loss

Active power transmission line loss is an essential factor to be taken into account for estimating the actual overall cost of the given generating system [13]. It can be obtained using the network loss formula as follows:

$$P_L = B_{00} + \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j + \sum_{i=1}^N B_{i0} P_i \quad (3.11)$$

4.1 Introduction

The scheduling problem for combined heat and power system of generation can be considered as composition of power dispatch and heat dispatch economically. Conventionally, economic load dispatch problem deals with the allocation of power ratings to the different generating units in an economical manner subjected to certain constraints. In a similar manner, CHPED problem involves the allocation of heat as well as power optimally for the purpose of meeting the required heat and power demands respectively subjected to both physical and technological constraints [29]. Civilized swarm optimization is a very powerful hybridized meta-heuristic approach and can be applied to solve CHPED problem.

4.2 Formulation of Objective Function

The problem includes conventional operating units and cogeneration units. The overall cost function can be represented as the summation of cost functions for all the units calculated separately as given below:

$$F(P, H) = \sum_{e=1}^E C_e(P_e) + \sum_{chp=1}^{CHP} C_{chp}(P_{chp}, H_{chp}) + \sum_{c=1}^C C_c(H_c) \quad (4.1)$$

subjected to various constraints as discussed in Eq. (3.5) to (3.10) in chapter 3.

4.2.1 Equality and inequality constraint handling

Civilized swarm optimization is an unconstraint searching optimization technique in which constraint handling feature must be incorporated from outside. Modern power systems suffer from the fluctuating demand problem and thus, uncertainty factors are more common in case of combined heat and power system rather than power dispatch problem. So it is necessary to satisfy equality constraint for heat and power as discussed in Eq. (3.5) and (3.6) and error corresponding to the equality constraint for power and heat can be computed as:

$$E1(P) = \begin{cases} (\sum_{i=1}^N (P_i - P_D - P_L))^2; & P_D + P_L \neq \sum_{i=1}^N P_i \\ 0 & ; P_D + P_L = \sum_{i=1}^N P_i \end{cases} \quad (4.2)$$

$$E1(H) = \begin{cases} (\sum_{i=1}^N (H_i - H_D)^2) & ; H_D \neq \sum_{i=1}^N H_i \\ 0 & ; H_D = \sum_{i=1}^N H_i \end{cases} \quad (4.3)$$

The inequality constraint requires the generation to lie within the working operational limits of the generating units for satisfactory performance and corresponding error to inequality constraint if the solution value lies outside the operational limits can be represented as follows:

$$E2(P) = \begin{cases} (P_{dp} - P_{dp}^{\max})^2 & ; P_{dp} > P_{dp}^{\max} \\ (P_{dp}^{\min} - P_{dp})^2 & ; P_{dp} < P_{dp}^{\min} \end{cases} \quad (4.4)$$

$$E2(H) = \begin{cases} (H_{dp} - H_{dp}^{\max})^2 & ; H_{dp} > H_{dp}^{\max} \\ (H_{dp}^{\min} - H_{dp})^2 & ; H_{dp} < H_{dp}^{\min} \end{cases} \quad (4.5)$$

4.2.2 Feasible operation region constraint

The feasible operating limits in case of cogeneration units include both power and heat in which both are functions of each other. Thus, it forms the complex inequality constraint which should be handled carefully for satisfactory operation of combined heat and power units within their capacity limits. Feasible operating region for a particular cogeneration unit is basically a graphical representation depicting the mutual dependence of heat and power on each other [19]. An irregular quadrilateral is a typical feasible operation region shown in figure 4.1.

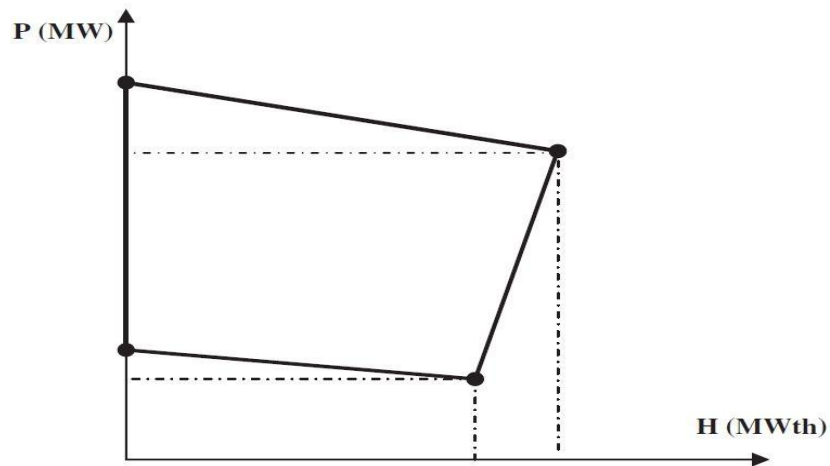


Fig 4.1 Feasible region of operation for cogeneration unit [11]

In this thesis work, Euclidean distance approach [23] is followed which indicates if the solution is not contained within the feasible region, violated values are made to contribute as penalty based on Euclidean distance in the objective function. If $(aH + bP + c = 0)$ represents the equation of shortest distance limit of the cogeneration unit and (H_o, P_o) represents output position of cogeneration unit, the minimum distance will be calculated using equation given below:

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

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

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

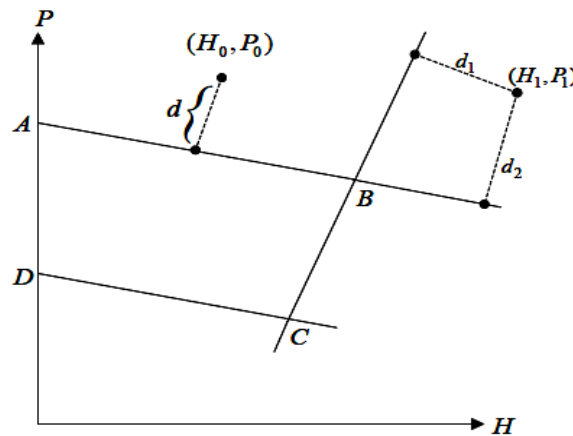


Fig. 4.2 Feasible region of operation indicating Euclidean distance penalty based approach [23].

If the point (H_1, P_1) lies at the corner of any boundary limit as shown, the error is calculated as the sum of distance between both the violated boundaries (d_1 and d_2) as indicated in figure [23].

4.2.3 Objective function

For the purpose of judging the proposed technique successful implementation on CHPED problem, the objective function for each unit in the civilization is evaluated. It is evaluated in such a way that objective function constituting overall generation cost including

the penalty (OF(P,H)) is minimized with proper handling of constraints. The objective function is obtained by adding cost function to the penalty based on euclidean distance approach as explained above obtained in Eq. (4.2). Thus, the objective is to minimize this obtained function value denoted as OF(P,H).

$$OF(P,H) = F(P,H) + r \times \text{error} \quad (4.8)$$

where $\text{error} = E1(P) + E1(H) + E2(P) + E2(H) + E(P,H)$ and 'r' represent a penalty parameter.

Following procedural steps are followed for the implementation of CSO for CHPED problem:

Step1 Parameter selection

The parameters used in CSO such as population size, social factor, cognitive factor, constriction factor, the boundary constraints, inertia weights and the maximum iterations to be carried out are selected.

Step2 Initialization of civilization

The individuals for all the heat and power units in the civilization are randomly generated individually as Eq. (2.1) based on their respective maximum and the minimum functional limits such that inequality constraints should be satisfied. This step must be followed for initialization of a feasible civilization vector.

Step3 Ascending order arrangement of the civilization

The objective function evaluated in Eq. (4.3) is then arranged in ascending order of its values and based on this arrangement, values of local best, velocity and position of each individual for all the heat and power units is arranged.

Step4 Identification of society leaders, society members and civilization leader

Above formed civilization for all the heat and power units is divided into three sections i.e. Society leaders which are first N_s individuals of the civilization as in Eq. (2.3), Society members which are remaining N_r members of the civilization as in Eq. (2.5) and civilization leader which is basically the first society leader having minimum value of objective function.

Step5 Society formation

Societies are formed based on the Euclidean distance approach. Euclidean distance is the minimum distance between a society member and a leader. Society member having minimum distance with a particular society leader is attached to the respective society for all the heat and power units civilization as in Eq. (2.6).

Step6 Updating velocities of formed society leaders, society members and civilization leader

The velocity up gradation for each of the society leaders, society members and civilization leader for all the heat and power units civilization is done using Eq. (2.12), (2.13) and (2.14). Similarly, the position of all the individuals is done following the same procedure as in Eq. (2.15), (2.16) and (2.17).

Step7 Checking the updated civilization for bound violations

Each dimension of an individual belonging to conventional units is checked for the limit violation which may get violated after civilization updating process and is made to follow the minimum and maximum limits as indicated in Eq. (2.1) i.e. if the solution is not within the functional limits, violated values are made to set at the nearest possible value on feasibility boundary.

Step8 Updating the best local values for each generating unit

The particles are updated to the best local position for all the heat and power units to improve the solution for each individual in population using the relations indicated in Eq. (2.9).

Step9 Stopping criterion

It is stopped based on the maximum count of iteration and if the condition for termination is not met, procedure is repeated from step 2. The power, heat and cogeneration value of the units corresponding to the minimum cost forms the optimal generation of each respective unit.

5.1 Introduction

Civilized swarm optimization has been implemented for scheduling the generation of combined heat and power system. The CSO algorithm has been tested on three sample test systems. Input data is indicated in Appendix A.

5.2 Case Study

The following cases have been studied: case study 1 for four generating units, case study 2 for twenty four generating units and case study 3 for forty eight generating units.

5.2.1 Case study 1

In this test system, four generating units are considered in which developed algorithm has been employed to solve the CHPED problem. This case includes one power only unit, one heat only unit and two cogeneration units. Power and heat demand for test system 1 are 200 MW and 115MWth [28]. The feasible operation region for the operating limits of cogeneration units are illustrated in fig 5.1 and 5.2. The full data for the respective system of power only and heat only units along with cost coefficients and operating limits taken from [28] are listed in table A.1 of appendix A.

5.2.2 Case study 2

A slightly more complex system is considered in case study 3 including thirteen power only units, five heat only units and six cogeneration units to check the operating performance of the proposed CSO technique. The power and heat demand for this case are 2350 MW and 1250 MWth respectively. The feasible regions of operation for the six cogeneration units are shown in Figure 5.1, 5.2 and 5.3. The complete data for this system adopted from [28] for conventional units and cogeneration units is given in table A.3 of appendix A.

5.2.3 Case study 3

In order to examine the computational performance for large scale power system, the proposed CSO technique is implemented on a standard forty eight units test system.

consisting of twenty six power only units, ten heat only units and twelve cogeneration units. Total power demand and heat demand considered in this case study is 4700 MW and 2500 MWth respectively. The feasible region of operation for the cogeneration units is indicated in Figure 5.1, 5.2, 5.3 and 5.4. The complete details for this system including conventional units and cogeneration units adopted from [28] are given in table A.4 of appendix A.

5.3 Simulation Results

The proposed research work has been carried out in the command line of FORTRAN-90 for the solution of CHPED problem using CSO. In order to obtain a stable and optimally operating solution, a number of trials for different values of CSO parameters is carried out i.e. at different value of acceleration constants (C_1 , C_{SL1} , C_{SL2} , C_{SM1} , C_{SM2}), inertia weight (w), maximum and minimum value of inertia weight (w^{\max} and w^{\min}), maximum iteration value and has been set for the optimally best solution given in table 5.1. Results are obtained by taking 50 particles and solved for 1000 iterations [28].

Table 5.1 Setting of parameter

S.NO.	Parameter	Value
1.	Swarm size	50
2.	Number of societies	4
3.	Inertia weight	$w^{\max} = 0.9$ and $w^{\min} = 0.4$
4.	Acceleration coefficients	$C_1 = 2$, $C_{SL1} = 0.5$, $C_{SL2} = 1.5$, $C_{SM1} = 0.25$, $C_{SM2} = 0.75$

The considered test system consists of conventional power unit, cogeneration units and conventional heat unit. It basically indicates the operating limits for a particular type of cogeneration system as shown from figure 5.1 to 5.4.

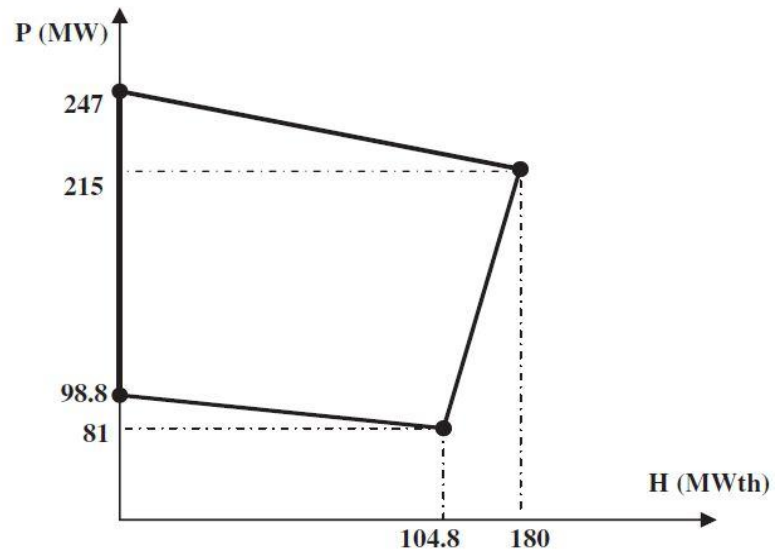


Fig 5.1 Feasible region of operation for the cogeneration unit of case study 1, 2, 3 and 4.

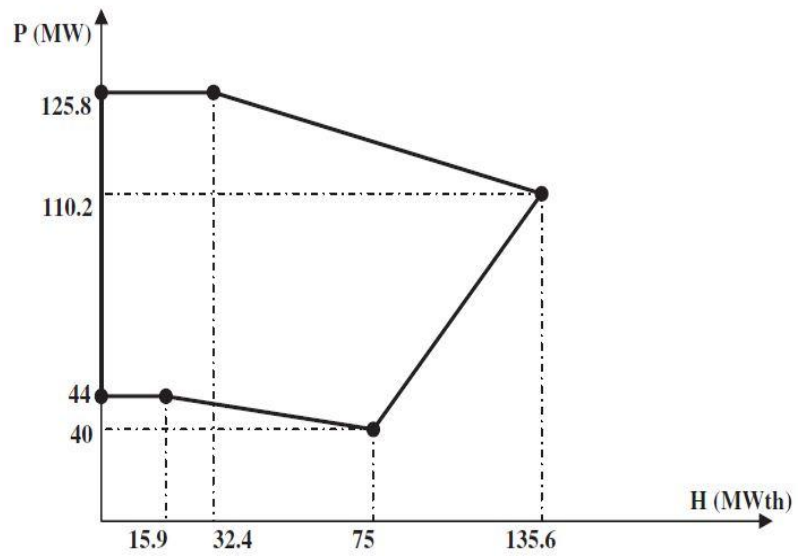


Fig 5.2 Feasible region of operation for the cogeneration unit of case study 1, 2, 3 and 4.

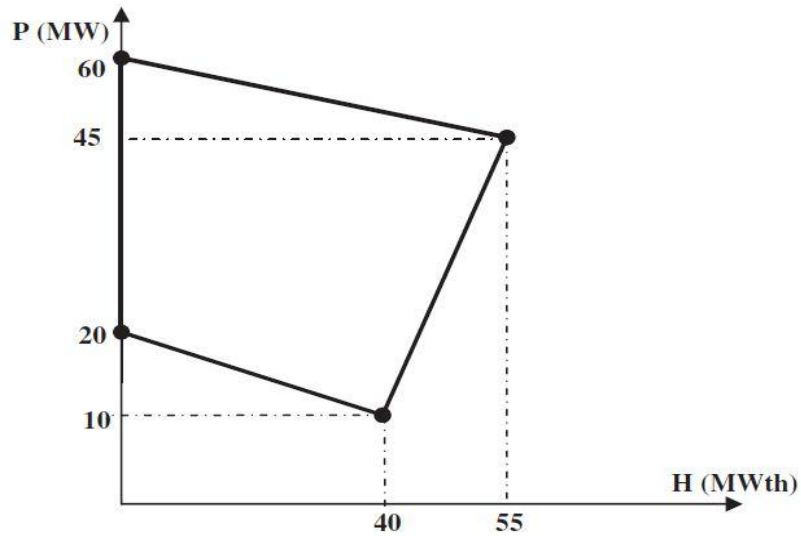


Fig 5.3 Feasible region of operation for the cogeneration unit 3 of case study 4.

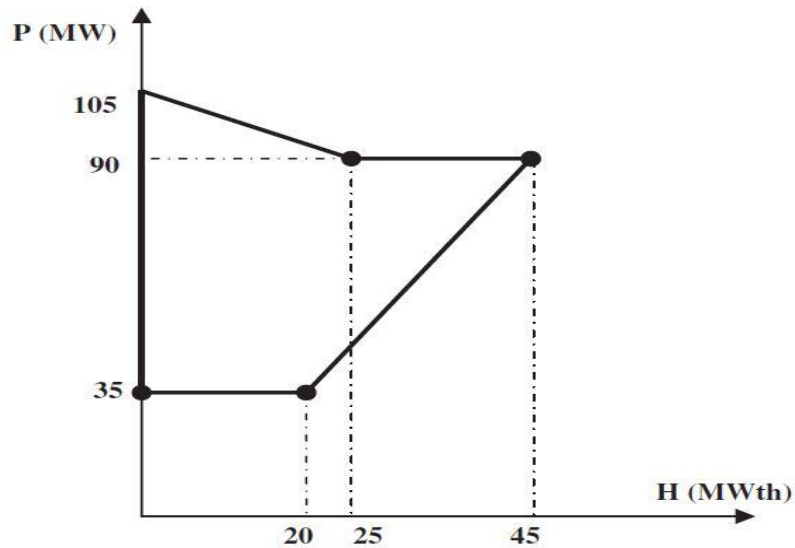


Fig 5.4 Feasible region of operation for the cogeneration unit 3 of case study 4.

In order to determine the effectiveness of CSO, different case studies has been carried out and results are compared with results obtained using other method on the same problem. Results thus obtained using CSO prove to be more satisfactory in comparison to those obtained using other conventional approaches, all constraints being satisfied [7]. The real power generations by each of the generating unit i.e. power, heat and combined heat and power are given in respective table.

Table 5.2 Operating cost comparison for case study 1

Control variables	RGA	GA_TABU	SGA	PSO	SPSO	CPSO	SAPSO	DPSO	ALHNN	IACSA	CSO
P_1 (MW)	0	0	0	0	0	0	0	0	0	0.08	0
P_2 (MW)	155.87	157.92	155.87	158.662	159.7065	159.4908	159.2452	158.964	159.99	150.93	159.9941
P_3 (MW)	44.13	42.08	44.42	40	40	40	40	40	40	48.84	40.00591
ΔP	0	200	.29	1.338	.2935	.5092	.7548	1.036	.01	.23	.00001
H_2 (MWth)	0.4	26	72.62	39.426	39.9097	39.4589	39.6720	39.723	39.9993	49	39.99487
H_3 (MWth)	112.64	89	42.38	75	75	75	75	75	75	65.79	75.0051
H_4 (MWth)	0	0	0	0	0	0	0	0	0	0.37	.0000305175
ΔH	1.96	0	0	.574	.0903	.5411	.328	.277	.0007	.16	.000000518
Feasible operation region violation	Yes (CG-3)	Yes (CG-3)	No	No	No	No	No	No	No	No	No
Cost(\$)	9151.07	9207.64	9168.67	9214.7	9248.17	9237.21	9233.10	9226.18	9257.05	9452.2	9257.122

where CG-3: Cogeneration unit 3; $\Delta P = \left| P_D - \sum_{i=1}^N P_i \right|$; $\Delta H = \left| H_D - \sum_{i=1}^N H_i \right|$; RGA: Revised GA; GA_TABU: GA tabu search; SGA: Simple GA; SPSO: Selective PSO; CPSO: Classic PSO; SAPSO: Simulated annealing PSO; DPSO: Discrete PSO; AIHNN: Artificial intelligence Hopfield neural network; IACSA: Improved ant colony search algorithm.

Table 5.3 Operating cost comparison for case study 2

Control variables	CPSO	TVAC_PSO	TLBO	OTLBO	CSO
P_1 (MW)	680	538.5587	628.3240	538.5656	287.6645
P_2 (MW)	0	224.4608	227.3588	299.2123	306
P_3 (MW)	0	224.4608	225.9347	299.1220	124.1689
P_4 (MW)	180	109.8666	110.3721	109.9920	98.68965
P_5 (MW)	180	109.8666	110.2461	109.9545	141.1089
P_6 (MW)	180	109.8666	160.1761	110.4042	113.7804
P_7 (MW)	180	109.8666	108.3552	109.8045	172.7477
P_8 (MW)	180	109.8666	110.5379	109.6862	147.9936

Table: 5.3(continued)

P₉(MW)	180	109.8666	110.5672	109.8992	137.8243
P₁₀(MW)	50.5304	77.5210	75.7562	77.3992	52.51924
P₁₁(MW)	50.5304	77.5210	41.8698	77.8364	106.8405
P₁₂(MW)	55.0000	120	92.4789	55.2225	104.4578
P₁₃(MW)	55.0000	120	57.5140	55.0861	80.92661
P₁₄(MW)	117.4854	88.3514	82.5628	81.7524	105.9028
P₁₅(MW)	45.9281	40.5611	41.4891	41.7615	131.1779
P₁₆(MW)	117.4854	88.3514	84.7710	82.2730	24
P₁₇(MW)	45.9281	40.5611	40.5874	40.5599	58.99772
P₁₈(MW)	10.0013	10.0245	10.0010	10.0002	77.95677
P₁₉(MW)	42.1109	40.4288	31.0978	31.4679	77.24259
ΔP	.227	.0002	.0001	.0004	.00012
H₁₄(MWth)	125.2754	108.9256	105.6717	105.2219	405.9403
H₁₅(MWth)	80.1175	75.4844	76.2843	76.5205	58.18779
H₁₆(MWth)	125.2754	108.9256	106.9125	105.5142	56.05336
H₁₇(MWth)	80.1174	75.484	75.5061	75.4833	120
H₁₈(MWth)	40.0005	40.0104	39.9986	39.9999	120
H₁₉(MWth)	23.2322	22.4676	18.2205	18.3944	100.0753
H₂₀(MWth)	415.9815	458.7020	468.2278	468.9043	122.8
H₂₁(MWth)	60	60	59.9867	59.9994	45.5
H₂₂(MWth)	60	60	59.9814	59.9999	22.53686
H₂₃(MWth)	120	120	119.6074	119.9854	94.01439
H₂₄(MWth)	120	120	119.6030	119.9768	104.8919
ΔH	.0001	.0004	0	0	.0001
Feasible operation region violation	No	No	Yes (CG-19)	Yes (CG-19)	No
Cost(\$)	59736.2635	58122.7460	58006.9992	57856.2676	62068.53

where CG-19: Cogeneration unit 19; TVAC_PSO: PSO with time varying acceleration coefficients; TLBO: Teaching learning based optimization; OTLBO: Oppositional TLBO.

Table 5.4 Operating cost comparison for case study 3

Control variable	CPSO	TLBO	OTLBO	CSO
P₁(MW)	359.0392	538.5693	628.3199	516.668
P₂(MW)	74.5831	225.3021	225.3313	0
P₃(MW)	74.5831	229.9473	223.9653	0
P₄(MW)	139.3803	159.1352	159.8516	60
P₅(MW)	139.3803	160.0561	109.9150	180
P₆(MW)	139.3803	109.7821	159.7795	147.1057
P₇(MW)	139.3803	159.6609	109.8946	180
P₈(MW)	139.3803	159.6492	109.9321	176.9643
P₉(MW)	139.3803	109.9660	159.9569	60
P₁₀(MW)	74.7998	40.3726	40.8970	120
P₁₁(MW)	74.7998	77.5821	41.3115	120
P₁₂(MW)	74.7998	92.2489	55.1748	98.242070
P₁₃(MW)	74.7998	55.1755	92.4003	55
P₁₄(MW)	679.8810	448.6854	448.8359	677.7224
P₁₅(MW)	148.6585	149.4238	225.7871	102.6129
P₁₆(MW)	148.6585	224.7173	75.4600	0
P₁₇(MW)	139.0809	109.9355	160.1192	163.7748
P₁₈(MW)	139.0809	159.9052	110.3532	0
P₁₉(MW)	139.0809	159.7255	159.8190	180
P₂₀(MW)	139.0809	159.7820	159.7765	177.916
P₂₁(MW)	139.0809	60.0777	159.7370	170.8432
P₂₂(MW)	139.0809	110.0689	160.1751	60
P₂₃(MW)	74.7998	77.6818	40.1140	104.931
P₂₄(MW)	74.7998	40.2707	40.3042	57.53488
P₂₅(MW)	112.1993	92.4108	92.4149	120
P₂₆(MW)	112.1993	55.0956	92.5012	100.7027
P₂₇(MW)	92.8423	81.4882	85.9857	81.14619

Table: 5.4(continued)

P₂₈(MW)	98.7199	44.5478	98.5005	110.461400
P₂₉(MW)	92.8423	81.0560	81.7197	164.570800
P₃₀(MW)	98.7199	91.6819	48.9055	154.486500
P₃₁(MW)	10.0002	10.5480	10.0832	20.66342
P₃₂(MW)	56.7153	52.7180	39.3110	30.17367
P₃₃(MW)	109.1877	82.1522	82.0236	88.2946
P₃₄(MW)	65.6006	52.0606	40.1105	54.50556
P₃₅(MW)	109.18	82.7394	81.3039	114.282
P₃₆(MW)	65.6006	45.7398	45.6700	62.54411
P₃₇(MW)	10.6158	10.0075	13.8709	60.69334
P₃₈(MW)	60.5994	30.0332	30.3881	68.16015
ΔP	18	178	200	.00031
H₂₇(MWth)	111.4458	105.0678	107.5951	361.3059
H₂₈(MWth)	125.6898	78.9162	125.4997	26.4452
H₂₉(MWth)	111.4458	104.8270	105.1942	60
H₃₀(MWth)	125.6898	119.6006	82.6853	120
H₃₁(MWth)	40.0001	40.2345	40.0346	102.1348
H₃₂(MWth)	29.8706	28.0508	21.9568	526.5526
H₃₃(MWth)	120.6188	105.4339	105.3622	58.12052
H₃₄(MWth)	97.0997	85.40864	75.0938	0
H₃₅(MWth)	120.6188	105.7694	104.9667	119.8955
H₃₆(MWth)	97.0997	79.9447	79.8936	120
H₃₇(MWth)	40.2639	40.0001	41.6554	104.882
H₃₈(MWth)	31.6361	17.7401	17.9018	121.3336
H₃₉(MWth)	357.9456	394.6160	445.0937	151.6994
H₄₀(MWth)	59.9916	59.9300	59.9967	146.0402
H₄₁(MWth)	59.9916	59.9578	59.9974	44.57004
H₄₂(MWth)	120	118.5797	119.8834	48.64585

Table: 5.4(continued)

H₄₃(MWth)	120	118.3425	119.5231	44.07637
H₄₄(MWth)	370.6214	480.6566	428.7605	28.86616
H₄₅(MWth)	59.9999	59.9346	59.9957	86.13433
H₄₆(MWth)	59.9999	59.9810	59.9638	80.21832
H₄₇(MWth)	119.9856	117.8207	119.5025	61.44
H₄₈(MWth)	119.9856	119.1898	119.4440	87.63911
ΔH	217.7184	.00244	.3603	.0001
Feasible operation region violation	No	Yes (CG-38)	Yes (CG-38)	No
Cost(\$)	119708.8818	116739.3640	116579.2390	128882.20

where CG-38: Cogeneration unit 38.

6.1 Conclusion

A hybridized meta-heuristic algorithm i.e. CSO for optimizing the CHPED problem has been suggested. Complication in the proposed problem lies in constraint handling process due to the imposed problem of mutual dependencies of heat and power and multi-demand system. The proposed method in this research work searches efficiently and results in exploitation of the optimal solution. The proposed method involves the integration of SCA and PSO such that it has the merits of both these algorithms. Euclidean distance based penalty factor is evaluated and finally merged to the objective function value for the purpose of well satisfaction and handling of constraints regarding feasible operating region. Thus, obtained numerical results indicate effectiveness of the proposed algorithm for solving the CHPED problem than all other previous techniques especially in case of large-scale problems in modern power system.

6.2 Scope for Future Work

The scope for work in future for improving the present case results using CSO is identified as:

- Civilized swarm optimization algorithm can use the concept of squeezing the velocity concept or k-factor based approach in its algorithm in order to improve the results.
- Civilized swarm optimization algorithm can be integrated with local search techniques.
- The applied technique can be applied on other real world power system optimization problems.
- The problem can be extended from multi-objective view point by considering emission as an objective.

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APPENDIX-A

Table –A.1

System data for case study 1

Conventional power unit										
Unit	P_{\min} (MW)	P_{\max} (MW)	a_i (\$/MW ²)	b_i (\$/MW)	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)	c_i (\$)	d_i (\$)	e_i (rad/MW)	f_i (\$)
2	81	247	0	180	2650	14.5	.0345	4.2	.03	.03
3	40	125.8	0	135.6	1250	36	.0435	0.6	.027	.01
Conventional heat unit										
Unit	H_{\min} (MWth)	H_{\max} (MWth)	a_i (\$/MW ²)	b_i (\$/MW)	c_i (\$)	d_i (\$)	e_i (rad/MW)			
4	0	2695.2	0	0	0	23.4	0			

Table –A.2

System data for case study 2

Conventional power unit							
Unit	P_{min} (MW)	P_{max} (MW)	a_i (\$/MW ²)	b_i (\$/MW)	c_i (\$)	d_i (\$)	e_i (rad/MW)
1	0	680	0.00028	8.1	550	300	.035
2	0	360	0.00056	8.1	309	200	.042
3	0	360	0.00056	8.1	309	200	.042
4	60	180	0.00324	7.74	240	150	.063
5	60	180	0.00324	7.74	240	150	.063
6	60	180	0.00324	7.74	240	150	.063
7	60	180	0.00324	7.74	240	150	.063
8	60	180	0.00324	7.74	240	150	.063
9	60	180	0.00324	7.74	240	150	.063
10	40	120	0.00028	8.6	126	100	.084
11	40	120	0.00028	8.6	126	100	.084
12	55	120	0.00028	8.6	126	100	.084
13	55	120	0.00028	8.6	126	100	.084

Table-A.2 (continued)

Cogeneration unit										
Unit	P_{\min} (MW)	P_{\max} (MW)	H_{\min} (MWth)	H_{\max} (MWth)	a_i (\$/MW ²)	b_i (\$/MW)	c_i (\$)	d_i (\$)	e_i (rad/MW)	f_i (\$)
14	81	247	0	180	.0345	14.5	2650	.03	4.2	.031
15	81	247	0	180	.0345	14.5	2650	.03	4.2	.031
16	10	60	0	55	0.1035	34.5	2650	.025	2.203	.051
17	35	105	0	45	0.072	20	1565	0.02	2.34	.04
18	40	125.8	0	135.6	.0435	36	1250	.027	.6	.011
19	40	125.8	0	135.6	.0435	36	1250	.027	.6	.011
Conventional heat unit										
Unit	H_{\min} (MWth)	H_{\max} (MWth)	a_i (\$/MW ²)	b_i (\$/MW)	c_i (\$)					
20	0	2695.2	0.038	2.0109	950					
21	0	60	0.038	2.0109	950					
22	0	60	0.038	2.0109	950					
23	0	120	0.052	3.0651	480					
24	0	120	0.052	3.0651	480					

Table –A.3

System data for case study 3

Conventional power unit							
Unit	P_{\min} (MW)	P_{\max} (MW)	a_i (\$/MW ²)	b_i (\$/MW)	c_i (\$)	d_i (\$)	e_i (rad/MW)
1	0	680	0.00028	8.1	550	300	.035
2	0	360	0.00056	8.1	309	200	.042
3	0	360	0.00056	8.1	309	200	.042
4	60	180	0.00324	7.74	240	150	.063
5	60	180	0.00324	7.74	240	150	.063
6	60	180	0.00324	7.74	240	150	.063
7	60	180	0.00324	7.74	240	150	.063
8	60	180	0.00324	7.74	240	150	.063
9	60	180	0.00324	7.74	240	150	.063
10	40	120	0.00028	8.6	126	100	.084
11	40	120	0.00028	8.6	126	100	.084
12	55	120	0.00028	8.6	126	100	.084
13	55	120	0.00028	8.6	126	100	.084
14	0	680	0.00028	8.1	550	300	.035
15	0	360	0.00056	8.1	309	200	.042

Table-A.3 (continued)

16	0	360	0.00056	8.1	309	200	.042			
17	60	180	0.00324	7.74	240	150	.063			
18	60	180	0.00324	7.74	240	150	.063			
19	60	180	0.00324	7.74	240	150	.063			
20	60	180	0.00324	7.74	240	150	.063			
21	60	180	0.00324	7.74	240	150	.063			
22	60	180	0.00324	7.74	240	150	.063			
23	40	120	0.00028	8.6	126	100	.084			
24	40	120	0.00028	8.6	126	100	.084			
25	55	120	0.00028	8.6	126	100	.084			
26	55	120	0.00028	8.6	126	100	.084			
Cogeneration unit										
Unit	P_{\min} (MW)	P_{\max} (MW)	H_{\min} (MWth)	H_{\max} (MWth)	a_i (\$/MW ²)	b_i (\$/MW)	c_i (\$)	d_i (\$)	e_i (rad/MW)	f_i (\$)
27	81	247	0	180	.0345	14.5	2650	.03	4.2	.031
28	81	247	0	180	.0345	14.5	2650	.03	4.2	.031
29	81	247	0	180	.0345	14.5	2650	.03	4.2	.031
30	81	247	0	180	.0345	14.5	2650	.03	4.2	.031
31	10	60	0	55	0.1035	34.5	2650	.025	2.203	.051

Table-A.3 (continued)

32	10	60	0	55	0.1035	34.5	2650	.025	2.203	.051
33	35	105	0	45	0.072	20	1565	0.02	2.34	.04
34	35	105	0	45	0.072	20	1565	0.02	2.34	.04
35	40	125.8	0	135.6	.0435	36	1250	.027	.6	.011
36	40	125.8	0	135.6	.0435	36	1250	.027	.6	.011
37	40	125.8	0	135.6	.0435	36	1250	.027	.6	.011
38	40	125.8	0	135.6	.0435	36	1250	.027	.6	.011
Conventional heat unit										
Unit	H_{\min} (MWth)	H_{\max} (MWth)	a_i (\$/MW ²)	b_i (\$/MW)	c_i (\$)					
39	0	2695.2	0.038	2.0109	950					
40	0	60	0.038	2.0109	950					
41	0	60	0.038	2.0109	950					
42	0	120	0.052	3.0651	480					
43	0	120	0.052	3.0651	480					
44	0	2695.2	0.038	2.0109	950					
45	0	60	0.038	2.0109	950					
46	0	60	0.038	2.0109	950					
47	0	120	0.052	3.0651	480					
48	0	120	0.052	3.0651	480					

