

Economic Dispatch Problem with Multiple Fuel by using Integrated Search Technique

A Dissertation submitted in fulfilment of the requirement for the Degree
of

MASTER OF ENGINEERING *in* **Power Systems**

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DECLARATION

I hereby certify that the work which is being presented dissertation entitled, “**Economic Dispatch Problem with Multiple Fuel by using Integrated Search Technique**” as a part of curriculum during Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried under the supervision of Dr. Nitin Narang and Ms. Manbir Kaur. It refers others researcher’s work which are duly listed in the reference section. The matter contained in this report has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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ABSTRACT

An integration of civilized swarm optimization (CSO) and shuffle frog leap algorithm (SFLA) is presented to solve practical economic load dispatch (ELD) problem. In the formulation of practical ELD problem, multiple fuel, valve point effect, transmission losses, ramp rate limits and prohibited operating zone are also considered. In CSO, societies are formed by the group of individual with better performing individual of each society consider as society leaders. The best performing society leader consider as civilization leader. In this proposed integrated search technique, initially the particles are updated by applying CSO algorithm thereafter SFLA update the worst particles and make the worst particles to better particles. This integrated search technique provides the fast convergence speed and best global solution. In this dissertation work, multi- fuel options have been considered due to depletion and ever increase in cost of quality. Due to these problems, multi- fuel options provide to the power plant and effect of the multi-fuel should be considered in ELD problem. To evaluate the efficiency and feasibility of proposed technique, it is applied to small, medium and large test systems. The better results are obtained by the proposed technique as compared to other optimization technique described in literature.

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NOMENCLATURE

i		Index of thermal generating units
j		Index of individual's particles
M		Number of particles
X_{ij}		Power output of i^{th} unit for the solution j^{th} particle
$X_{ij}^{min}, X_{ij}^{max}$		Minimum and maximum output power of the unit i^{th} for the solution j
t		Number of iterations
N_s		Total number of society leaders of the civilization
SL, CL, SM		Society leader, civilization leader and society member, respectively
N_R		Society members of the civilization
PF_T		Objective value
r, k		Individual of society member and society leader of the civilization, respectively
D_r		Euclidean distance
V_{iL}, V_{ik} and V_{ir}		Velocity of civilization leader, society leader and society member of i^{th} unit
w, w^{max}, w^{min}		Inertia weight, initial weight and final weight, respectively
r_1, r_2, r_3, r_4, r_5		Random numbers
$C_L, C_{SL_1}, C_{SL_2}, C_{SM_1}, C_{SM_2}$		Acceleration coefficients for the CL, SL and SM
X_L, X_{SLk}, X_{SMr}		Updated positions of the CL, SL, SM
$M_m^{best}, P^{best}, M_m^{worst}$		Best performer, global best performer and worst performer particles
$F_T, F_i(P_i)$		Total fuel cost and fuel cost function of the i^{th} unit
P_i, P_D		Output power of the i^{th} unit, total demand
P_i^{min}, P_i^{max}		Minimum and maximum value of P_i
$a_{in}, b_{in}, c_{in}, e_{in}$ and f_{in}		Fuel cost coefficients of the i^{th} unit using the fuel type n
P_{in}		Output power of i^{th} unit with n^{th} fuel type
P_T		Total power

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ABBREVIATIONS

CSO	Civilized Swarm Optimization
SCA	Society Civilized Algorithm
PSO	Particle Swarm Optimization
SFLA	Shuffle Frog Leap Algorithm
NN-EPFO	Neural Network-Efficient Particle Swarm Optimization
EP-EPFO	Evolutionary Programming-Efficient Particle Swarm Optimization
CGA_MU	Conventional Genetic Algorithm with Multiplier Updating
EP	Evolutionary Programming
IBA	Improved Bat Algorithm
SA	Simulated Algorithm

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Chapter-1

Introduction

1.1 Overview

Electrical energy is the most important form of energy. The demand of the energy is increasing day by day and conventional energy source such as coal, oil, gas etc. are reducing every day. It is important to be aware about the proper use of the fuels. In the power systems, the economic load dispatch (ELD) is the major problem of the optimization. ELD is one of the most demanding tasks in any power systems because conventional energy sources are depleting day by day and cost is increasing. The objective of ELD is maximizing the utilization of generation at lowest cost while satisfying the load demand and generation limits. The ELD problem with multiple fuel is to minimize the total cost of the fuel among the present fuel for each generator while satisfying the all constraints. The generators are supplied with the multiple fuel options to determine the most economic fuel to burn. Practically, the input output characteristics of the generating units are non-linear due effect of valve point effect, ramp rate limits (RRL) and prohibited operating zone (POZ). The valve point loading effect provide the discontinuities and non-linearity in the cost curve, the cost function is expressed as a segmented piecewise non-linear function [1] as compared to single quadratic function. The generating units may have restricted zone due to effect of physical limitation of machine component, steam valve and vibration in shaft bearing. Such restricted zone is known as POZ. Generally, due to RRL the operating ranges of all online generating units is barred hence to determine the optimal solution of ELD, multi- fuel options and practical constrained should be taken into account.

Conventional methods such as Lagrange relaxation method, linear programming methods, dynamic programming have been applied on ELD problem. Most conventional techniques can guarantee to reach optimal solution but it is not guarantee to reach global solution. Metaheuristic techniques come forward to overcome the drawback of conventional techniques. Metaheuristic technique can find the global solutions with minimum computational effort as compared to conventional techniques. Metaheuristic techniques such as civilized swarm optimization (CSO), society civilized algorithm (SCA), shuffle frog leap algorithm (SFLA), particle swarm optimization (PSO), bee algorithm exploit the local solution and provide the global solution. CSO and SFLA can obtain a good result after sufficient iteration. CSO takes the advantage of PSO and SCA where PSO is used for the exploration for the local solution and SCA exploit the local solution and provide the global solution. SFLA use the properties

of PSO and memetic algorithm (MA) where MA has strong local search capability and PSO has better global search ability. In this dissertation work, integration of CSO and SFLA has been applied to solve ELD problem and compared with other optimization techniques described in literature using five test systems.

1.2 Review of Literature

The conventional and metaheuristic techniques have been applied on ELD problem. Li *et al.* [2] applied Lagrange relaxation with multiplier updates to solve dynamic ELD problem. Multiplier updates was based on the quasi-newton method. Ray [3] solved the ELD problem by applying interval based approach called as interval gradient method. Dieu *et al.* [4] applied augmented Lagrange hopfield network to solve the ELD problem with emission, transmission constraint and ramp rate. Reddy *et al.* [5] solved the ELD problem with transmission system and active power constrained by introducing an improved HNN.

In the ELD problems, metaheuristic techniques provide the better results as compare to conventional techniques. Sinha *et al.* [1] applied an evolutionary programming (EP) technique to solve the ELD problems. Walters *et al.* [6] introduced genetic algorithm (GA) to solve the ELD problem with valve point loading effect. Aristidis [7] applied an ant colony optimization to solve ELD problem. Pandian *et al.* [8] applied two hybrid algorithm evolutionary programming efficient particle swarm optimization and neural network efficient particle swarm optimization to solve non convex ELD problem. Coelho and Lee [9] introduced the chaotic and Gaussian particle swarm optimization to solve the ELD problem. Panigrahi *et al.* [10] solved the ELD problem by applying firefly algorithm (FA). Bindu *et al.* [11] applied cuckoo search algorithm (CSA) to solve the ELD problem. Gherbi *et al.* [12] solved the ELD problem by applying bat algorithm (BA). This hybrid technique applied on ELD problem where CSA increased the exploitation capability and CRO technique provided the better exploration of the solution. Subathra *et al.* [13] applied hybrid technique to solve ELD problem by considering valve point loading effect. This hybrid technique was integrated of cross-entropy (CE) and sequential quadratic programming (SQP) method where SQP performed as a local search and combination of CE-SQP provided the global result.

Multiple fuels options provided the benefits to control the sources of fuels such as (coal, gas, oil) and economical solutions. Conventional techniques used for the ELD with multi-fuel provided the poor results as compare to metaheuristic algorithm. Lee *et al.* [14] solved the ELD problem with multiple fuel and non-linear constraints by applying enhanced Lagrange neural network. Thang [15] presented a technique hopfield Lagrange network to

solve the ELD problem by considering multiple fuel options. Lin and Viviani [16] solved ELD problem with piecewise quadratic cost function by using hierarchical numerical method. Park *et al.* [17] solved ELD problem with piecewise quadratic cost function by using HNN.

There is no guarantee to reach global solution by conventional techniques, hence metaheuristic algorithms are used to obtain global results because it solves non-linear and non-convex problems in convenient way. Chiang [18] solved the ELD problem with multiple fuel options and valve- point loading effect by applying improved GA with multiplier updating. Multiplier updating is used to control the equality and inequality constraints of the ELD. Park *et al.* [19] applied improved PSO to solve ELD problem with multiple fuel options and valve point loading effect. Hassan *et al.* [20] solved the non-convex ELD problem by applying modified PSO and GA. Suresh *et al.* [21] examined the effect on the ELD problems by the practical constraints and multiple fuel. A uniform distributed two-stage PSO technique used to solve this problem. Vijayaraj *et al.* [22] obtained good results of ELD with multi-fuel options and valve point loading effect by applying improved bat algorithm. Krishnasamy *et al.* [23] minimized the cost for the dynamic ELD with Integrated Multi-fuel and wind power plant by using A Refined Teaching-Learning Based Optimization Technique.

Hybrid algorithms provide the better result as compare to other technique. To solve the large scale optimization problem, hybrid technique provides the better solution because it is the combination of two strategies and overcome the disadvantage of one another. Narang *et al.* [24] applied integrated civilized swarm optimization and powell's search method to solve the combined heat and power economic dispatch problem. Jiang *et al.* [25] applied PSO-SFLA and UWB technique to increase the performance of recognition rate.

CSO is a hybrid algorithm and takes the advantage of both PSO and SCA properties. PSO provide the global results in less time, but the results obtain by the PSO trapped into local minima hence PSO does not provide the optimal solution. The combination of SCA and PSO improve the exploitation and provide the global solution. CSO has been applied on various optimization problems and it provides the satisfactory results compare to other techniques. Tapabrata *et al.* [26] presented the SCA to solve the single objective constrained optimization problems. Selvakumar *et al.* [27] obtained the solution for ELD with multiple minima by using CSO technique. Selvakumar *et al.* [28] applied CSO to solve the multi-objective short-term hydrothermal scheduling problem. Narang [29] minimized the cost of the thermal unit by proper use of water resources and improved predator influenced CSO algorithm used to solve this problem.

Metaheuristic techniques play a major role to solve the optimization problems. But hybrid techniques as compare to any other techniques provide the better global solution. SFLA is a hybrid technique which take the advantage of PSO and MA. SFLA has been applied for various optimization problems and it provide the good results. Chen [30] solved the bi-objective problem such as combined economic emission dispatch by the help of SFLA. Yun *et al.* [31] improved the performance of heterogeneous multiprocessor by using SFLA. Singh *et al.* [32] maintained the voltage stability when the load shaded from the specify load bus at the emergency condition considered equality and inequality constrained, the optimize load shaded was obtained by using SFLA. Saedeh *et al.* [33] minimized the two type of cost, investment cost of new lines and loss of load cost in the transmission expansion planning by using SFLA. Hasanien [34] applied SFLA on photovoltaic model identification to obtain the unknown parameters of the single diode photovoltaic model. Jaballah *et al.* [35] improved the efficiency of SFLA by applied two search- acceleration factor. Anita *et al.* [36] applied SFLA to solve the environmental constrained unit commitment problem. Darvishi *et al.* [37] improved the power factor and reduce harmonic by using SFLA.

1.3 Objective of the Work

The objective of dissertation is to obtain the optimal solution of practical ELD with constrained satisfaction by applying proposed integrated search technique with and without considering multi-fuel, valve point effect, transmission losses, RRL and POZ. The proposed technique implemented in dissertation work utilises the properties of CSO and SFLA. Both CSO and SFLA is a metaheuristic technique. In the proposed technique, initially the particles are updated by applying CSO algorithm thereafter SFLA update the worst particles and make the worst particles to better particles. The proposed technique provides the fast convergence speed and better global result as compared to CSO and SFLA and also prove to be better as compared to other optimization technique.

1.4 Organization of Dissertation

The dissertation entitled as “Economic Dispatch Problem with Multiple Fuel by using Integrated Search Technique” has been summarized in six chapters. **Chapter 1** mentions detailed overview, brief literature review related to problem and dissertation objective. **Chapter 2** provides overview of integrated search technique, detailed about CSO and SFLA. **Chapter 3** introduces about problem formulation of ELD, multiple fuel, valve point effect, RRL and POZ. **Chapter 4** highlight integrated search technique implemented on practical ELD

problem. **Chapter 5** show and discuss the results from different types of test system. **Chapter 6** mentioned conclusion of dissertation work, scope for future work, references section and appendix

Chapter-2

Integrated Search Technique

2.1 Introduction

In the economic load dispatch (ELD) problems, there are various algorithms have been applied on ELD problems. However, every algorithm has own advantages and disadvantages hence integrated search techniques overcome the disadvantages of one algorithm by another algorithm. Civilized swarm optimization (CSO) and shuffle frog leap algorithm (SFLA) is a hybrid technique. Both algorithm has own advantages and disadvantages. CSO is a hybrid of particle swarm optimization (PSO) and society civilized algorithm (SCA). Properties of both PSO and SCA are used in the CSO which fairly maintains the exploration of local search areas and exploiting these areas to provide global results [29]. In CSO, PSO updates the velocity and position of the particles based on personal best experience of the swarms and best particles are followed by the remaining of the particles in the case of SCA. SFLA is the combination of memetic algorithm (MA) and PSO. SFLA use the properties of both PSO and MA. In SFLA, MA has strong local search capability and PSO has better global search ability. In SFLA, PSO updates the velocity and position of the worst particles based on personal best experience of the swarms and then make the worst particles to better performing particles. CSO fulfils the necessary requirement of a meta-heuristic technique in which the solution of the best particles is followed solution of the rest particles [29] and SFLA improve the worst particles hence the integration of CSO and SFLA provide the fast convergence speed and better global solution. This Integrated search technique can be applied to any ELD problem

2.2 Civilized Swarm Optimization

Metaheuristic techniques are capable to obtain global solution by exploiting the local search results. CSO is a metaheuristic which is hybrid of PSO and SCA techniques which is used as optimizer to solve the various optimization problems. It obtains the better result due to interaction between each particle of the swarm because interaction between particles increase the chance to obtain good result.

In CSO, each particle is divided in different societies depend on the relative coordination. Each society consider a society leader; all society members follow the society leaders [28]. The best performing particle among the society leaders is considered as civilization leader. All the society leaders follow the civilization leader and improve themselves according to civilization

leader. The society members and society leaders of all the society make the civilization. All the society members improve themselves according to society leaders and all the society leaders improve themselves according to civilization leader [28]. The best performer between all the particles provide the global best solution. The initialization of each particle in the swarm and velocity updating is similar to that of PSO. The procedure of identification of society leaders and society members is similar to that of SCA. The Euclidian distance between the society leaders and society members is calculated using equation (2.7). A particular society member is added in the society if the Euclidian distance between society member and society leader of that society is minimum. The best performer society leader is considered as civilization leader for a particular iteration.

Step-1 Initialization

Each particle of the civilization is represented by a set of all decision variables in the searching areas. Each particle of the civilization is produced randomly with maximum and minimum limit. If there are np units, each particle is mentioned as a vector of length np . Then each particle of the civilization is represented as a matrix. i.e.

$$civ(t) = [X_1, X_2, \dots, X_j, \dots, X_M] \quad (2.1)$$

where M is number of particles

$$X_j = [X_{1j}, X_{2j}, \dots, X_{npj}] \quad (2.2)$$

$$X_{ij}^{min} \leq X_{ij} \leq X_{ij}^{max} \quad (i=1, \dots, np; j=1, \dots, M) \quad (2.3)$$

where X_{ij} is the power output of i^{th} unit for the solution j , X_{ij}^{min} and X_{ij}^{max} minimum and maximum output power of the i^{th} unit for the solution j , t represent the number of iteration

Step-2 Objective function evaluation

Calculate the objectives value corresponding to individual's decision variable

Step-3 Selection of society leaders

Each particle of civilization is arranged in ascending order corresponding to objective values and the first N_s particles are considered as society leaders.

$$SL(t) = [SL_1, SL_2, \dots, SL_{N_s}] \quad (2.4)$$

where SL represent society leader

Step-4 Selection of civilization leader

Society leader with minimum objective value is considered as civilization leader. If $t=1$ then objective value is considered as $PF_T(CL(t))$, and if $t \neq 1$ then,

$$objective(t) = \begin{cases} PF_T(CL(t)), & \text{if } objective(t-1) > PF_T(CL(t)) \\ PF_T(CL(t-1)), & \text{if } objective(t-1) \leq PF_T(CL(t)) \end{cases} \quad (2.5)$$

where CL represent civilization leader

Step-5 Selection of society members

The remaining particles of the civilization after the selection of society leaders are considered as society members. All the society members in the civilization is represented as $SM(t)$. The set of society members is represented by N_R , i.e. $N_R = M - N_S$

$$SM(t) = [SM_1, SM_2, \dots, SM_{N_R}] \quad (2.6)$$

where SM represent society member

Step-6 Formation of societies

Societies formation depends on the Euclidean Distance (D_r). The Euclidean Distance is determined between society leaders and society members based on each SM_r belongs to $SM(t)$.

$$D_r = \sum_{i=1}^{np} (SM_{ir}(t) - SL_{ik}(t))^2 \quad (k = 1, 2, \dots, N_S ; r = 1, 2, \dots, N_R) \quad (2.7)$$

Step-7 Velocity update of SL , SM and CL

The velocity of civilization leader (CL), society leader (SL) and society member (SM) are updated by following equations:

For civilization leader:

$$V_{iL}(t+1) = w \times V_{iL}(t) + C_L \times r_1 \times (P_{iL}^{best}(t) - CL_i(t)) \quad (i=1, 2, \dots, np) \quad (2.8)$$

$$\text{where } w = w^{max} \times \frac{w^{max} - w^{min}}{it_{max}} \times it$$

where, it_{max} is the maximum number of iteration, w is the inertia weight, w^{max} and w^{min} is initial and final weight.

For society leaders:

$$V_{ik}(t+1) = w \times V_{ik}(t) + C_{SL_1} \times r_2 \times (P_{ik}^{best}(t) - SL_{ik}(t)) + C_{SL_2} \times r_3 \times (CL_i(t) - SL_{ik}(t)) \\ (i=1, 2, \dots, np ; k=1, 2, \dots, N_S) \quad (2.9)$$

For society members

$$V_{ir}(t+1) = w \times V_{ir}(t) + C_{SM_1} \times r_4 \times (P_{ir}^{best}(t) - SM_{ir}(t)) + C_{SM_2} \times r_5 \times (SL_{ik}(t) - SM_{ir}(t)) \\ (i=1, 2, \dots, np ; k=1, 2, \dots, N_S ; r = 1, 2, \dots, N_R) \quad (2.10)$$

where V_{iL} , V_{ik} and V_{ir} is the velocity of civilization leader, society leaders and society members of i^{th} unit, r_1, r_2, r_3, r_4, r_5 are random numbers which are uniformly distributed in the range

of 0 to 1 and $C_L, C_{SL_1}, C_{SL_2}, C_{SM_1}, C_{SM_2}$ are the acceleration coefficients for the CL, SL and SM which help to obtain better global solution.

The best position P^{best} for civilization leader, society leaders and society members are updated by using equations (2.12), (2.13) and (2.14). The swarm of the civilization for the next generation is considered as an empty set. Then for the next iteration, civilization leader is directly considered into the new civilization:

$$X_L(t+1) = CL(t) + V_L(t+1) \quad (2.11)$$

all the society leaders which are follow the civilization leader also considered into the new civilization:

$$X_{SLk}(t+1) = SL_k(t) + V_{SLk}(t+1) \quad (2.12)$$

$$X_{SMr}(t+1) = SM_r(t) + V_{SMr}(t+1) \quad (2.13)$$

where X_L, X_{SLk} and X_{SMr} are the updated positions of the civilization leader, society leaders and society members

2.3 Shuffle Frog Leap Algorithm

To solve the optimization problems, various searching techniques have been applied that provide the global solution. SFLA is a search technique based on the social behaviour of the frog, invented by Eusuff and Lansey in 2000 [38] which, improve the worst particles and make the worst particles to better particles and provide the better global result. In SFLA, the global solution is achieved by exchange of information between each frog (particle). SFLA is a hybrid of MA and PSO, it takes the advantage of exploration by PSO [39] and add the information from parallel local search to provide global result [40]. In SFLA, the set of the frog is considered as population [41]. Individual frog can represent the better solution and it is divided into subset called as memeplexes. Each group of memeplexes must be consider as different culture of frogs and it is provided the local result. SFLA is a technique which improves the worst particle at every iteration and make the worst particles as better performers.

Step-1 Initialization

The initialization process of SFLA is similar as discuss in CSO algorithm in equations (2.1) (2.2) and (2.3).

Step- 2 Memeplex formation

Different culture of frogs are divided into memeplexes and frogs in the different memeplexes are arranged in ascending order based on the objective value, then find the best performer particles (M_m^{best}) for all the memeplexes and also find the global best performer P^{best} .

Step-3 Update the worst frogs position

Each memplex is used for the local exploration. Worst performer particles (M_m^{worst}) are updated by the following equation:

$$D_m = r_1 \times (M_m^{best} - M_m^{worst}) \quad (m=1,2,\dots,N) \quad (2.14)$$

where N is number of memplexes.

The limit of D_m must be lie between maximum and minimum value of D_m , otherwise set between D_{min} and D_{max} . r_1 is the random number varying between the 0 and 1. The new position of the worst particles is improved by the equation as:

$$M_m^{worst}(new) = M_m^{worst}(old) + D_m \quad (m=1,2,\dots,N) \quad (2.15)$$

Now, calculate the objective values of updated particles

Step- 4 Comparison between objectives

If the objective value of the $M_m^{worst}(new)$ is lower than the objective value of $M_m^{worst}(old)$ then consider objective value of $M_m^{worst}(new)$, otherwise calculate D_m with respect to P^{best} .

$$D_m = r_1 \times (P^{best} - M_m^{worst}) \quad (m=1,2,\dots,N) \quad (2.16)$$

The limit of D_m must be lie between maximum and minimum value of D_m , otherwise set between D_{min} and D_{max} . The new position of worst particles is calculated by:

$$M_m^{worst}(new) = M_m^{worst}(old) + D_m \quad (m=1,2,\dots,N) \quad (2.17)$$

Then again calculate the objective values of updated worst particles.

If the objective value of the $M_m^{worst}(new)$ is lower than the objective value of $M_m^{worst}(old)$ then consider the objective value of $M_m^{worst}(new)$, otherwise replace M_m^{worst} by generate randomly new particles within the maximum and minimum limits.

Repeat Step-3 and step-4 for update worst particles position for all the memplexes. Now shuffle the particles according to step-2

Step-5 Termination

If iteration reach to the maximum value of iteration, then the process of optimization is stop, otherwise, repeat the process from step-2 with increase the iteration.

Chapter-3

Practical Economic Load Dispatch Problem

3.1 Economic Load dispatch

The main objective of economic load dispatch (ELD) is to obtain the optimal power generation of generators involving in providing the load and also to minimize the fuel cost by fulfilling the following practical constrained:

- To meet load demand
- Maximum and minimum generation limits of each generator

The economic load dispatch problem problems consider to belong the category of large scale non- linear constrained optimization problem [21]. When conventional approaches are applied for this problem then there is no guarantee to achieve global solution because large scale non- linear constrained optimization problem make the problem difficult to solve. Meta-heuristic techniques such as GA, PSO, BAT, CSO, SFLA are come forward to solve these non- linear problems. Meta-heuristic techniques provide the global solution without trapped into local solutions.

3.2 Problem Formulation

The economic load dispatch problem is referred as to minimize the total fuel cost without constrained violation. The ELD can be defined as optimization method with objective [42].

$$\min F_T = \sum_{i=1}^{np} F_i(P_i) \quad (3.1)$$

where F_T is the total fuel cost, $F_i(P_i)$ is described the fuel cost function of the i^{th} unit. P_i is the output power of i^{th} unit, np is defined as the number of units.

It is important to consider the multi- fuel options such as coal, gas, oil etc. because every day, the level of the fuel is decrease and the cost of the fossil fuel is increases. Due to these problems, multi- fuel options provide to the power plant and effect of the multi-fuel should be considered in ELD problem. The units should supply with the multi-fuel sources because it provides the most economical fuel to burn for ELD. Multiple cost curves with any given unit must need to operate on the lower contour of the intersecting curves then the resulting cost function is known as “hybrid cost function”. [22]. Which fuel should be burn, its depend on the hybrid cost function because individual piece of hybrid cost function mention some knowledge about the fuel being burned

ELD problems without valve point loading effect provide the approximation solution because cost curve is so much non-linear and consist of discontinuities due to valve point effect.

The cost function is segmented piecewise quadratic nonlinear function compare to single quadratic function. The ELD problems provide the accuracy in solution by considering valve point loading effect. The combination of multiple fuel options and valve point loading effect provide the realistic operation of ELD. If a unit with n fuel options, then cost function of ELD with multiple fuel and valve point loading effect can be expressed as:

$$F_i(P_i) = \begin{cases} c_{i1} + b_{i1} * P_i + a_{i1} * P_i^2 + |e_{i1} * \sin(f_i * (P_{i1}^{min} - P_{i1}))| \\ c_{i2} + b_{i2} * P_i + a_{i2} * P_i^2 + |e_{i2} * \sin(f_i * (P_{i2}^{min} - P_{i2}))| \\ \vdots \\ c_{in} + b_{in} * P_i + a_{in} * P_i^2 + |e_{in} * \sin(f_i * (P_{in}^{min} - P_{in}))| \end{cases} \quad (3.2)$$

$$\text{Fuel 1- } P_i^{min} \leq P_i \leq P_{i1}$$

$$\text{Fuel 2- } P_{i1} \leq P_i \leq P_{i2} \quad (3.3)$$

:

$$\text{Fuel n- } P_{in-1} \leq P_i \leq P_i^{max}$$

where a_{in} , b_{in} , c_{in} , are fuel cost coefficients of the i^{th} unit using the fuel type n, e_{in} and f_{in} are fuel cost coefficients due to valve point effect of the i^{th} unit using the fuel type n, the unit of a_{in} is $\$/MW^2hr$, b_{in} is $\$/MWhr$ and c_{in} is $\$/hr$.

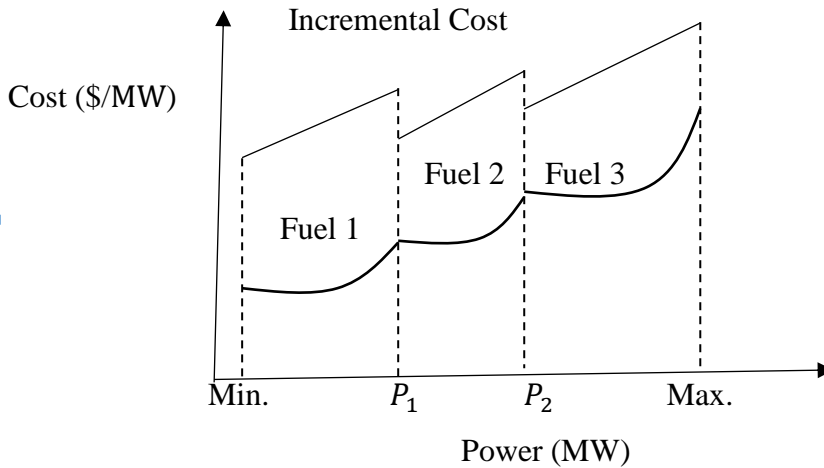


Fig 3.1: Hybrid Cost and Incremental Cost Function

Multiple fuel options can be applied in thermal generating units; hence, the objective function can be expressed with piecewise quadratic function reflecting the effect of change in fuel type (Eq-3.2). The cost and incremental cost function are represented in Fig 3.1.

To minimize the total fuel cost, total power output must equal to total demand and transmission losses.

$$\sum_{i=1}^{np} P_i = P_D + P_L \quad (i=1,2,\dots, np) \quad (3.4)$$

where P_D is the total demand in MW and P_L is the transmission network losses

$$P_i^{min} \leq P_i \leq P_i^{max} \quad (i=1,2,\dots, np) \quad (3.5)$$

$$P_L = \sum_{i=1}^{np} \sum_{j=1}^{np} P_i B_{ij} P_j \quad (i=1,2,\dots, np; j=1,2,\dots, np) \quad (3.6)$$

where P_i^{min} , P_i^{max} are the minimum and maximum value of P_i and B_{ij} is the transmission loss coefficients. The B- matrix is given in A.2.1 of appendix A

3.2.1 Ramp-rate limits and Prohibited operating zones

Practically, the power generated in certain level cannot be exceed to the previous interval by more than the up-rate limit (UR_i) and also it cannot less than to the previous interval by more than the down-rate limit (DR_i) of the generator. These provide the following constraints.

if generation increases

$$P_i - P^0 \leq UR_i \quad (i=1,2,\dots, np) \quad (3.7)$$

if generation decreases

$$P_i - P^0 \geq DR_i \quad (i=1,2,\dots, np) \quad (3.8)$$

where P_i is present time generated power, P^0 is the previously generated power, UR_i and DR_i is the up-rate limit and down-rate limit in MW/time-interval.

The inclusion of ramp-rate limits changes the generator operation constraints such as:

$$\max(P_i^{min}, P^0 - DR_i) \leq P_i \leq \min(P_i^{max}, P^0 + UR_i) \quad (3.9)$$

The generating units consist of prohibited operating zones (POZ) by the effect of steam valve operation or vibration in the shaft bearing. If generated power lies in POZ and near to the upper limit of the POZ, then consider the upper limit. If generated power is near to lower limit of the POZ, then take the lower limit.

The feasible operating zones of the i^{th} unit can be described as:

$$P_i^{min} \leq P_i \leq P_{i,1}^L \quad (3.10)$$

$$P_{i,k-1}^U \leq P_i \leq P_{i,k}^L \quad (k=2,3,\dots, n_i) \quad (3.11)$$

$$P_{i,n_i}^U \leq P_i \leq P_i^{max} \quad (3.12)$$

where k is the number of POZ of the i^{th} unit, n_i is the total number of POZ of the i^{th} unit, L and U represent the lower and upper limit of the POZ.

Chapter-4

Implementation of Integrated Search Technique

4.1 Introduction

In the practical economic load dispatch (ELD) problems, for a realistic problem it is important to consider the multiple fuel, valve point loading effect, transmission losses, ramp rate limits and prohibited zones. ELD problem with multiple fuel provides the most economical fuel to use. In this work, integration of civilization swarm optimization (CSO) and shuffle frog leap algorithm (SFLA) is applied to solve the practical ELD problem.

4.2 Formulation of objective function

The objective function is formulated by considering the total generation cost. The objective function is expressed as:

$$\text{Objective } (PF_T) = F_T + r \times \text{error}^2 \quad (4.1)$$

$$\text{error} = \sum_{i=1}^{np} P_i - (P_D + P_L) \quad (4.2)$$

where r is the penalty factor, F_T is the total fuel cost, P_i is the i^{th} generator output power, P_L is the transmission network losses, np is defined as the number of units and P_D is the total demand.

4.3 Implementation

Following are the steps of implementation of integrated search technique to solve ELD problems:

Step-1 Selection of Parameters

The good selections of parameters are important to provide optimal generation schedule in any optimization problems. Population size, inertia weights, social factor, cognitive factor, constriction factor and boundary constraints are the parameters.

Step-2 Initialization of Civilization

The power of the individuals is randomly generated in the civilization by using equation (2.2) within minimum and maximum limits of the power

Step-3 Evaluation of objective function

The objective function values are obtained by using equation (4.1), then the values of the objective functions are arranged in ascending order

Step-4 Selection of society leaders, society members, civilization leader

Society leaders, society members and civilization leader formed the civilization. The first N_s values corresponding to minimum objective function are considered as society leaders as in equation (2.4), the remaining N_r values are considered as society members as in equation (2.6). Society leaders with minimum objective function is considered as civilization leader.

Step-5 Update the velocity and position of particles

The velocity of society leaders, society members and civilization leader are updated by using equations (2.9), (2.10) and (2.8). Similarly, positions are updated by using equations (2.12), (2.13) and (2.11). The new objectives function values are calculated of the updated values of positions by using equation (4.1).

The comparison of new objective values and old objective values are depended on the minimum objective values. After comparison rearrange the objective values then selection of the *SL*, *SM* and *CL* is based on the minimum objective function.

Step-6 Society formation

Societies formation depend on the Euclidian distance between *SL* and *SM* and it is calculated using equation (2.7). A particular society member is added in the society if the Euclidian distance between society member and society leader of that society is minimum.

Step-7 Update the worst particles by SFLA

Calculate the distance between best particles and worst particles by using equation (2.14) then update the worst performer particles by using equation (2.15)

Calculate the objective values of the updated worst particles by using equations (4.1). Then compare between updated worst particles objective values and old worst particles objective values. If objective values of updated worst particles are lower than the objective values of old worst particles, then considered the updated worst particles objective values otherwise calculate the distance between global best value and worst particles by using equation (2.16) then update the worst particles by using equation (2.17)

Evaluate the objective values of new updated worst particles. If objective values of new updated worst particles are lower than the objective values of old worst particles, then considered the new updated worst particles objective values otherwise replace old worst particles by generating randomly new particles within the maximum and minimum limits then

calculate the objective values correspond to randomly generate new particles. Now shuffle the particles position

Step-8 Termination

If iteration reach to the maximum value of iteration, then the process of optimization is stop, otherwise, repeat the process from step-4.

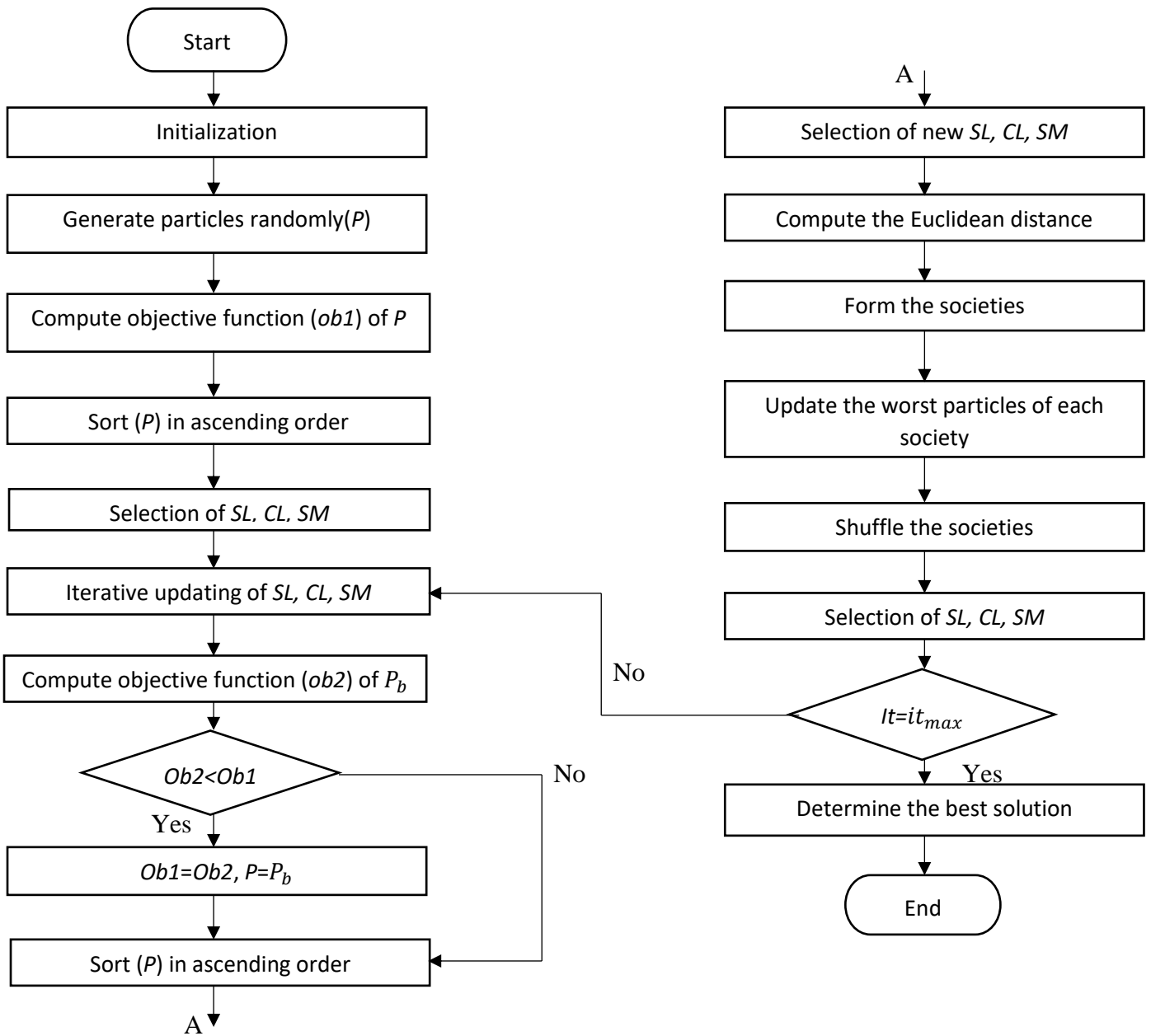


Fig. 4.1: Flow chart of Integrated Search Technique

Chapter-5

Results and Discussion

5.1 Introduction

The proposed integrated search technique has been implemented for solving the practical economic load dispatch (ELD) problem by considering multiple fuel, valve point loading effect, transmission losses, ramp rate limits (RRL) and prohibited operating zone (POZ). Five test systems have been considered in this study. The test systems (1-5) have considered the thermal units. The input data for the test systems is mentioned in Appendix A.

5.2 Test systems

Integrated search technique has been tested on five test systems. Where, test system-1 &2, test system-3, test system-4 and test system-5 have three thermal units, thirteen thermal units, forty thermal units and ten thermal units. The system characteristics are given in [6], [8], [18] and [44] and listed in table (A.1-A.5) of Appendix A.

Table 5.1 Summary of test systems

Test system	POZ	Ramp rate limits	Valve point effect	Transmission loss	Multiple fuel option
1	No	No	Yes	No	No
2	Yes	Yes	No	Yes	No
3	No	No	Yes	No	No
4	Yes	Yes	No	No	No
5	No	No	Yes	No	Yes

Table 5.2 provides the information about which test system have POZ, RRL, Valve point effect, Transmission loss and Multiple fuel option.

5.3 Simulation Result for Integrated Search Technique

The Fortran-90 language is used to solve the practical ELD problem by using integration of CSO and SFLA. The parameters of the integrated search technique have been investigated for different value of acceleration coefficients, maximum and minimum value of inertia weight w^{max} and w^{min} value are given in table 5.2.

In order to examine the performances of proposed algorithm, the results published in literature [6], [8], [18], [22], [43] and [44] are considered. The generations of real power by individual generating unit are given in table (5.3-5.6) whereas fuel type by individual generating unit are given in table 5.7.

Table 5.2 Parameter setting for Integrated Search Technique

S.NO.	Parameter		Test system-1	Test system-2	Test system-3	Test system-4	Test system-5
1	Swarm size		100	100	100	100	100
2	No. of Societies		4	4	5	4	5
3	Inertia weight	w^{max}	0.9	0.9	0.9	0.9	0.9
		w^{min}	0.4	0.4	0.4	0.4	0.4
4	Acceleration coefficients	C_L	1.5	1.5	2.0	2.0	2.0
		C_{SL_1}	0.5	0.5	0.5	0.5	0.5
		C_{SL_2}	1.0	0.45	0.54	0.33	0.46
		C_{SM_1}	0.25	0.25	0.25	0.25	0.25
		C_{SM_2}	0.75	0.75	0.50	0.50	0.55

Table 5.3 Comparison of results for test sytem-1

Power (MW)	Proposed Integrated Search technique	SFLA	CSO	GA[6]
P_1	301.1874	400.0099	300.6076	300
P_2	399.2130	400.0000	399.6000	400
P_3	149.5995	50.0000	149.8000	150
P_D	850	850	850	850
P_T	850	850.0099	850.0076	850
F_T (\$/h)	8236.9170	8341.3230	8292.6590	8237.6

Table 5.4 Comparison of results for test sytem-2

Power (MW)	Proposed Integrated Search technique	SFLA	CSO	GA[43]	2-phase neural network [44]
P_1	227.5035	235.6572	238.6959	194.265	165
P_2	49.79882	30.4079	41.30418	50.0	113.4
P_3	36.81813	51.4883	34.0000	79.627	34.0
P_D	300	300	300	300	300
P_T	314.1204	317.5534	314.0001	324.011	312.45
P_L	14.1204	17.5534	14.0001	24.011	12.45
F_T (\$/h)	3649.2930	3828.8270	3655.8820	3737.2	3652.6

Table 5.5 Comparison of results for test sytem-3

Power (MW)	Proposed Integrated Search Technique	SFLA	CSO	SA [8]	NN EPSSO [8]	EP EPSSO [8]
P_1	626.5559	680.0000	680.0000	668.40	680.0000	680.0000
P_2	309.0828	360.0000	360.0000	359.78	360.0000	360.0000
P_3	298.9303	360.0000	360.0000	358.20	265.0000	360.0000

Table-5.5 (Continued)

P_4	159.8316	180.0000	180.0000	104.28	72.0000	180.0000
P_5	160.7263	172.8049	172.8049	60.36	165.0000	150.3476
P_6	161.8272	103.5926	180.0000	110.64	159.0000	151.2105
P_7	126.7449	135.6625	60.0000	162.12	171.0000	149.6332
P_8	159.9096	121.2108	83.2384	163.03	116.0000	149.8140
P_9	148.4667	144.2142	173.9603	161.52	89.0000	148.9940
P_{10}	88.61444	45.01023	40.0000	117.09	104.0000	40.0000
P_{11}	97.64366	56.86801	120.0000	75.00	99.0000	40.0000
P_{12}	85.28082	86.82512	55.0000	60.00	120.0000	55.0000
P_{13}	96.38691	73.81674	55.0000	119.58	120.0000	55.0004
P_D	2520	2520	2520	2520	2520	2520
P_T	2520.001	2520.0050	2520.0040	2520.00	2520.0000	2520.0000
F_T (\$/h)	24774.74	25562.750	25331.990	24970.91	24738.6563*	24050.1519*

*From the generation schedule the correct result of NN EPSSO and EP EPSSO are **25529.9** and **25113.03**

Table 5.6 Comparison of results for test sytem-4

Power (MW)	Proposed Integrated Search Technique	SFLA	CSO
P_1	42.09863	47.73784	60.52923
P_2	61.25629	85.0000	71.60125
P_3	159.4715	172.9903	169.7911
P_4	36.07747	29.26342	35.94995
P_5	41.35978	35.43859	28.56765
P_6	108.7669	80.76372	87.60294
P_7	127.0453	119.0956	140.4692
P_8	188.6017	162.6689	204.7260
P_9	185.3700	170.8567	257.6820
P_{10}	149.6565	152.1059	153.4510
P_{11}	281.9868	294.6644	315.0034
P_{12}	224.4008	313.5630	266.1492
P_{13}	142.3894	199.8415	220.1520
P_{14}	235.1411	191.5557	262.5137
P_{15}	150.2497	230.0000	157.6070
P_{16}	230.2700	156.7083	213.3316
P_{17}	188.9528	142.2931	182.0371
P_{18}	331.7791	440.4423	452.2469
P_{19}	392.3500	433.9641	374.4418
P_{20}	431.0000	409.6639	431.0000
P_{21}	444.5797	374.4438	431.0000
P_{22}	432.2575	382.9803	355.5103
P_{23}	327.8152	364.4407	300.6192
P_{24}	391.3588	353.0789	324.1761
P_{25}	370.0000	352.7963	312.7542
P_{26}	377.2401	410.0000	305.8018
P_{27}	445.1400	312.6258	410.0000
P_{28}	29.88596	85.45654	24.9355
P_{29}	37.33133	45.85858	28.76301

Table-5.6 (continued)

P_{30}	34.43463	47.8574	28.84587
P_{31}	50.42773	47.17521	59.2179
P_{32}	67.34843	37.25784	26.97877
P_{33}	36.65986	36.38268	32.4224
P_{34}	21.78844	32.6871	42.87234
P_{35}	33.69548	30.89347	43.58204
P_{36}	42.76883	37.26883	37.17918
P_{37}	46.98812	46.07748	48.69252
P_{38}	34.70561	35.50805	32.58187
P_{39}	40.37938	45.01557	38.90722
P_{40}	26.96261	53.61637	30.30392
P_D	7000	7000	7000
P_T	6999.9920	7000.0390	6999.9980
F_T (\$/h)	107850.40	114306.30	108414.20

Table 5.7 Comparison of results for test sytem-5

Methods	Proposed Integrated Search Technique	SFLA	CSO	CGA_MU [18]	EP [18]	IBA [22]
Unit (MW)	Fuel Gen. Type	Fuel Gen. Type	Fuel Gen. Type	Fuel Gen. Type	Fuel Gen. Type	Fuel Gen. Type
P_1	2 219.8545	1 132.7830	2 250.0000	2 222.0108	2 225.2	2 231.4150
P_2	1 211.1485	1 182.4885	1 230.0000	1 211.6352	1 215.6	1 226.3850
P_3	1 286.3866	2 452.2177	1 305.5910	1 283.9455	1 291.8	1 297.3150
P_4	3 238.4969	3 230.3519	2 174.6091	3 237.8052	3 242.1	3 237.4850
P_5	1 275.5879	1 299.6025	1 190.4900	1 280.4480	1 293.7	1 280.5950
P_6	3 244.0718	3 208.6523	3 234.8721	3 236.0330	3 241.9	3 236.5850
P_7	1 285.0461	1 260.5235	2 344.6582	1 292.0499	1 301.6	1 292.6550
P_8	3 238.8119	3 233.3040	3 253.8695	3 241.9708	3 242.8	3 241.7650
P_9	3 422.5025	1 335.1575	3 440.0000	3 424.2011	1 356.6	3 407.1550
P_{10}	1 278.0937	3 364.9202	1 275.9092	1 269.9005	1 288.7	1 248.6450
P_D	2700	2700	2700	2700	2700	2700
P_T	2700	2700	2699.999	2700	2700	2700
F_T (\$/h)	624.6785	669.4897	653.5204	624.7193	626.26	621.13*

*From the generation schedule the correct result is **627.1641**

For the test system-5, 30 independent runs were executed to quantify the results. The total number of particles were 100 and the number of iterations was 1000. It is clear from the table 5.8 that standard deviation (S.D) and the average of number of objective function evaluations (NFE's) of proposed integrated search technique is less as compared to CSO and SFLA.

Table 5.8 Comparison of S.D and NFE for test system-5

Technique	Min. Cost (\$/hr)	Avg. Cost (\$/hr)	Worst Cost (\$/hr)	S.D	NFE (Avg.)
CSO	653.5204	715.0123	768.8773	30.9339	43430
SFLA	669.4897	720.4722	792.7865	32.1270	61390
Proposed	624.6785	674.0001	696.4374	16.2269	43413

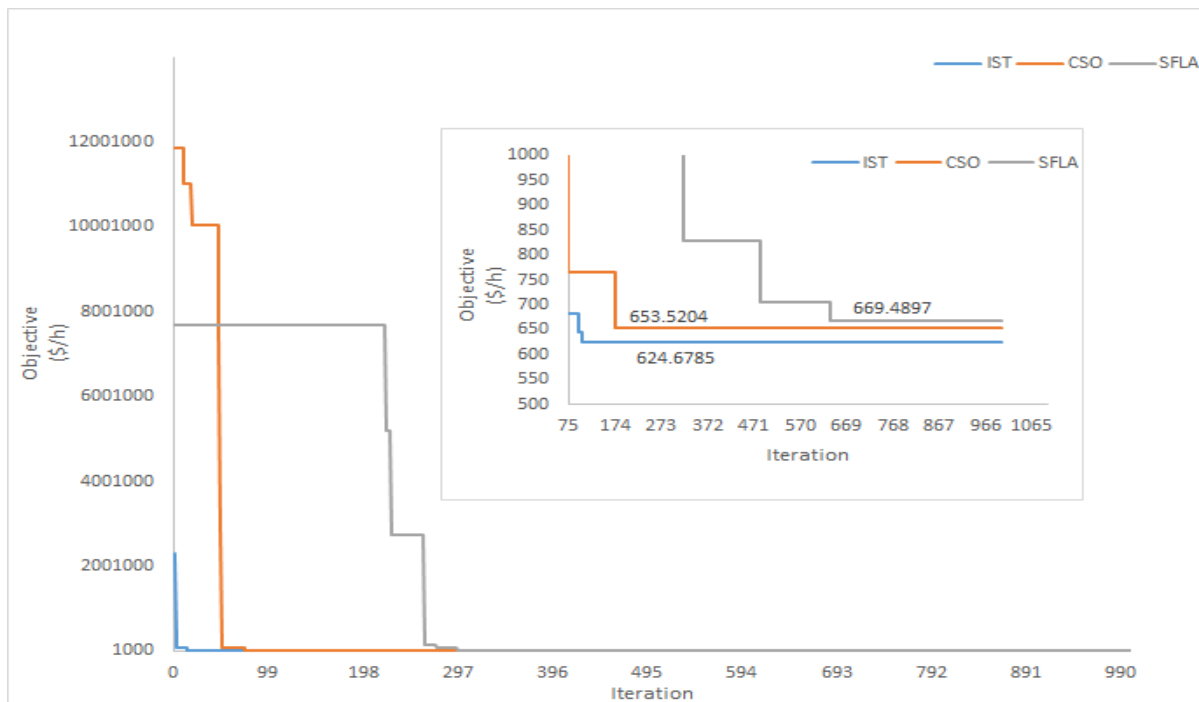


Fig 5.1: Convergence Characteristics for test system-5

It is clear from the convergence characteristics that the integrated search technique is converged at early iterations and provide the better solution as compared to CSO and SFLA.

Chapter-6

Conclusion and Future Scope of the Work

6.1 Conclusion

A new proposed integrated search technique is developed by integration of civilized swarm optimization (CSO) and shuffle frog leap algorithm (SFLA) to solve economic load dispatch (ELD) problem with and without multiple fuel, valve point loading effect, transmission losses, ramp rate limits and prohibited zone. In the proposed technique, CSO update the all particles then provide the best particles whereas SFLA update the worst particles and make the worst particles to better particles. The CSO and SFLA provide the poor solutions, whereas proposed integrated search technique provide the quality solutions consistently for ELD problem with practical constrained. The integrated search technique provides the fast convergence speed and better global solution as compared to CSO and SFLA. Proposed integrated search technique outperforms the CSO and SFLA and provide the following advantages:

- Better searching capability for solving ELD problems
- Superior robustness as compared to CSO and SFLA

6.2 Future Scope

The scope for the future work in the dissertation is recognised as:

- The problem of the ELD can be extended from one objective to multi-objective by considering emission as an objective.
- The problem of ELD can be dynamic.

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APPENDIX-A

System data for test system-1

Table-A.1 ($P_D=850\text{MW}$)

Unit	P_{min} (MW)	P_{max} (MW)	Cost coefficients				
			$a_i(\times 10^{-2})$	$b_i(\times 10^1)$	$c_i(\times 10^3)$	$e_i(\times 10^3)$	$f_i(\times 10^{-1})$
1	100	600	0.1562	.792	.5610	.300	.315
2	100	400	0.194	.785	.310	.200	.42
3	500	200	0.482	.797	.078	.150	.63

System data for test system-2

Table-A.2 ($P_D=300\text{MW}$)

Unit	P_{min} (MW)	P_{max} (MW)	Cost coefficients			P^0 (MW)	UR_i (MW)	DR_i (MW)	POZ
			a_i ($\times 10^{-2}$)	b_i ($\times 10^2$)	c_i ($\times 10^3$)				
1	50	250	0.525	.08663	.32813	215	55	95	[105,117], [165,177]
2	5	150	0.609	.1004	.13691	72	55	78	[50,60], [92,102]
3	15	100	0.592	.0976	.05916	98	45	64	[25,32], [60,67]

A.2.1 Loss coefficients matrix (B-matrix)

$$B_{ij} = \begin{bmatrix} 0.000136 & 0.0000175 & 0.000184 \\ 0.0000175 & 0.000154 & 0.000283 \\ 0.000184 & 0.000283 & 0.00161 \end{bmatrix}$$

System data for test system-3

Table-A.3 ($P_D=2520\text{MW}$)

Unit	P_{max} (MW)	P_{min} (MW)	Cost coefficients				
			$a_i(\times 10^{-2})$	$b_i(\times 10^1)$	$c_i(\times 10^3)$	$e_i(\times 10^3)$	$f_i(\times 10^{-1})$
1	680	0	.0280	.810	.550	.300	.350
2	360	0	.0560	.81	.309	.200	.420
3	360	0	.0560	.810	.307	.150	.420
4	180	60	.324	.774	.240	.150	.63
5	180	60	.324	.774	.240	.150	.63
6	180	60	.324	.774	.240	.150	.63
7	180	60	.324	.774	.240	.150	.63
8	180	60	.324	.774	.240	.150	.63
9	180	60	.324	.774	.240	.150	.63
10	120	40	.284	.860	.126	.100	.84
11	120	40	.284	.860	.126	.100	.84
12	120	55	.284	.860	.126	.100	.84
13	120	55	.284	.860	.126	.100	.84

System data for test system-4

Table-A.4 ($P_D=7000\text{MW}$)

Unit	P_{max} (MW)	P_{min} (MW)	Cost coefficients			UR (MW)	DR (MW)	P^0 (MW)	POZ
			a_i	$b_i(10^2)$	$c_i(10^4)$				
1	80	40	0.03073	.08336	.017044	35	60	80	-
2	120	60	0.2028	.070706	.030954	40	70	120	[80,85]
3	190	80	0.00942	.081817	.036903	50	90	190	[82,88]
4	42	24	0.08482	.069467	.013548	42	42	24	-

Table-A.4(continued)

5	42	26	0.09693	.065595	.013519	42	42	42	-
6	140	68	0.01142	.080543	.022233	40	75	75	-
7	300	110	0.0357	.080323	.028771	65	100	100	[155,162],[221,235]
8	300	135	0.00492	.06999	.039198	65	100	152	-
9	300	135	0.00573	.06602	.045576	65	100	200	[235,246]
10	300	130	0.00605	.12908	.072282	65	100	100	[200,211]
11	375	94	0.00515	.12986	.06352	55	95	300	[213,220]
12	375	94	0.00569	.12796	.065469	55	95	300	[213,220]
13	500	125	0.00421	.12501	.09134	80	120	150	[201,211],[290,310], [413,425]
14	500	125	0.00752	.088412	.17604	80	120	200	[205,217],[306,318], [409,420]
15	500	125	0.00708	.091575	.17283	80	120	190	[214,230],[277,290], [402,412]
16	500	125	0.00708	.091575	.17283	80	120	190	[214,230],[277,290], [402,412]
17	500	125	0.00708	.091575	.17283	80	120	190	[214,230],[277,290], [402,412]
18	500	220	0.00313	.079691	.064785	70	110	400	[307,321],[407,421]
19	500	220	0.00313	.07955	.064969	70	110	400	[301,310],[421,431]
20	500	242	0.00313	.079691	.064783	70	110	398	[340,351],[421,431]
21	500	242	0.00313	.079691	.064781	70	110	398	[340,351],[421,431]
22	550	254	0.00298	.066313	.078596	70	110	390	[306,320],[440,445]
23	550	254	0.00298	.066313	.078596	70	110	390	[306,320],[440,445]
24	550	254	0.00284	.066611	.079453	70	110	390	[370,390],[495,502]
25	550	254	0.00284	.066611	.079453	70	110	390	[370,390],[495,502]

Table-A.4(continued)

26	550	254	0.00277	.071032	.080132	70	110	390	[380,410],[501,520]
27	550	254	0.00277	.071032	.080132	70	110	390	[380,410],[501,520]
28	150	10	0.52124	.033353	.10551	90	150	20	[102,113]
29	150	10	0.52124	.033353	.10551	90	150	20	[102,113]
30	150	10	0.52124	.033353	.10551	90	150	30	[102,113]
31	70	20	0.25098	.13052	.12078	70	70	30	-
32	70	20	0.16766	.21887	.81079	70	70	40	-
33	70	20	0.26350	.10244	.12477	70	70	40	-
34	70	20	0.30575	.083707	.12192	70	70	25	-
35	60	18	0.18362	.26258	.064143	60	60	25	-
36	60	18	0.32563	.096956	.11128	60	60	20	-
37	60	20	0.33722	.071633	.10444	60	60	20	-
38	60	25	0.23915	.16339	.083224	60	60	25	-
39	60	25	0.23915	.16339	.083424	60	60	25	-
40	60	25	0.23915	.16339	.10352	60	60	25	-

System data for test system-5Table-A.5 ($P_D=2700\text{MW}$)

unit	Generation			Fuel Type	Cost coefficients				
	P_{min} F_1	F_2	P_{max} F_3		$a_i(10^{-2})$	$b_i(10)$	$c_i(10^3)$	$e_i(10^0)$	$f_i(10^2)$
1	100	196	250	1	.2176	-.03975	.02697	.02697	-.03975
	1	2		2	.1861	-.03059	.02113	.02113	-.03059
2	50	114	157	1	.4194	-.1269	.1184	.1184	-.1269
	2	3	1	2	.1138	-.003988	.001865	.001865	-.003988
				3	.1620	-.01980	.01365	.01365	-.01980

Table-A.5(continued)

3	200 332 388 500	1	.1457	-.03116	.03979	.03979	-.03116
	1 3 2	2	.001176	.04864	-.05914	-.05914	.04864
		3	.08035	.003389	-.002875	-.002876	.003389
4	99 138 200 265	1	.1049	-.003114	.001983	.001983	-.003114
	1 2 3	2	.2758	-.06348	.05285	.05285	-.06348
		3	.5935	-.2338	.2668	.2668	-.2338
5	190 338 200 265	1	.1066	-.008733	.01392	.01392	-.008733
	1 2 3	2	.1597	-.05206	.09976	.09976	-.05206
		3	.01498	.04462	-.05399	-.05399	.04462
6	85 138 200 265	1	.2758	-.06348	.05285	.05285	-.06348
	2 1 3	2	.1049	-.003114	.001983	.001983	-.003114
		3	.5935	-.2338	.2668	.2668	-.2338
7	200 331 391 500	1	.1107	-.01325	.001893	.01893	-.01325
	1 2 3	2	.1165	-.02267	.04377	.04377	-.02267
		3	.2454	.03559	-.04335	-.04335	.03559
8	99 138 200 265	1	.1049	-.003114	.001983	.001983	-.003114
	1 2 3	2	.2758	-.06348	.05285	.05285	-.06348
		3	.5935	-.2338	.2668	.2668	-.2338
9	130 213 370 440	1	.1554	-.05675	.08853	.08853	-.05675
	2 1 3	2	.7033	-.004514	.01530	.01423	-.001817
		3	.06121	-.001817	.01423	.01423	-.001817
10	200 362 407 490	1	.1102	-.009938	.01397	.01397	-.009938
	1 3 2	2	.04164	.05084	-.06113	-.06113	.05084
		3	.1137	-.02024	.04671	.04671	-.02024

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