DYNAMIC ECONOMIC LOAD DISPATCH

USING

DIFFERENTIAL EVOLUTION ALGORITHM

A Thesis submitted in partial fulfillment of the requirements for the award of degree of

Master of Engineering
In
Power System and Electric Drives

Thapar University, Patiala

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CERTIFICATE

I hereby certify that the work which is being presented in this Thesis entiled, "**Dynamic Economic Load Dispatch Using Differential Evolution**" in partial fulfillment of the requirements for the award of degree of **Master of Engineering in Power Systems and Electric Drives at Thapar University, Patiala,** is an authentic record of my own work carried out under the supervision of **Mr. Nirbhowjap Singh, Assistant Professor (EIED)** and **Mr. Nitin Narang, Assistant Professor (EIED)**. The matter embodied in this Thesis has not been submitted for the award of any other degree to any other university.

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

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I | P a g e

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ABSTRACT

Dynamic Economic Load Dispatch (DELD) is a real time problem of electric power system. DELD intends to schedule the online generators outputs with the predicted load demand over a certain period of time in order to operate an electric power system most economically within its security limits.

Differential Evolution (DE) is very effective for solving optimization problems with non-smooth and non-convex characteristics. This technique combines simple arithmetic operator with classic evolutionary operators, such as mutation, crossover and selection. The key idea behind DE is a scheme for generating trial vectors. Mutation is used to generate a mutant vector by adding differential vectors obtained from the difference of several randomly chosen parameter vectors to the parent vector. After that, a trial vector is produced by a crossover through recombining the obtained mutant vector with the target vector. In this thesis work, DE technique has been applied to solve DELD.

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CHAPTER 1 INTRODUCTION

1.1 Introduction

The basic static economic dispatch (SED) problem is to minimize the total generation cost among the committed units satisfying all unit and system equality and inequality constraints. Dynamic economic dispatch (DED) is a real time power system problem. The output power generation of each unit is determined with respect to predicted load demand over a period satisfying the unit and system constraints and ramp-rate constraint. To overcome this difficulty, DED is implemented which takes into account the dynamic costs involved in changing from one generation level to the other. However, most of them have considered the cost characteristics to be linear in nature in order to simplify the mathematical formulation of the problem and to allow many of the conventional optimization techniques to be used. In reality, the input–output characteristic of generating units are non-linear due to valve-point loading and more advanced algorithms are worth developing to obtain accurate dispatch results. Over recent years, there are many advancement occurs in economic dispatch [1], which are discussing practical approach to real time economic dispatch considering fuel cost dynamics [2], ramp rate limits [3], unit`s prohibited zone [4], spinning reserve constrained [5] etc. There were a number of traditional, advance and hybrid methods that have been applied to solve ED problems such as interior point method [6], fast computation Hopfield method [7], adaptive Hopfield neural network [8], dynamic programming (DP) [9], decision trees [10], fuzzy decision trees [11], radial basis function network [12], bender`s decomposition [13], dual quadratic programming (QP) [14], pattern search method [15], genetic algorithm (GA) [16], particle swarm optimization (PSO) [17-19], evolutionary programming [20], differential evolution (DE) [21-22], hybrid GA based on DE [23], combination of chaotic DE and QP [24], hybrid DE with biogeography-based optimization [25] and hybrid interior point assisted DE algorithm [26].

Dynamic Economic Dispatch of generation [27-28] considers different aspects such as feasible and optimal solutions [29]. Different features of DED in deregulated system are discussed [30]. There were a number of traditional, advance and hybrid methods that have been applied to solve DED problem such as homogeneous solution [31], approximation reasoning method [32], constructive DP [33], extended security constrained method [34], non-dominated sorting GA-2 [35], artificial immune system (AIS) [36-37], enhance bee swarm optimization [38], DE [39], novel bi-population chaotic DE [40], reserve constrained [41] and hybrid EP and SQP [42].

Differential Evolution is a population-based stochastic search technique that works in the general framework of evolution algorithms mainly based on mutation operator [43-44]. There are number of systems for which DE is used such as large capacitor placement problem [45], solving network reconfiguration of distribution systems [46], optimal reactive power flow [47] and transient stability constrained optimal power flow [48].

Literature Review

Economic Dispatch problem of power system is to determine the optimal combination of power outputs for all generating units, which minimizes the total fuel cost while satisfying the constraints. Ramp rates are the maximum rates specified for each unit at which the power output of a unit can be increased (ramp up rate) or decreased (ramp down rate) in a time interval. Violation of generation ramp rates will shorten the life of the rotor and therefore has to be satisfied in a practical system operation where the generation changes with demand.

Chowdhury and Rahman [1] have presented various aspects of ED. Yoshikawa, *et al.* [2] have proposed online economic load dispatch (ELD) based on fuel cost dynamics. The purpose of ELD is to determine power demands of individual generators so that total fuel cost of those generators may be minimized. Wang and Shahidehpur [3] have proposed an algorithm for unit commitment and ED problem to consider the ramp characteristics in starting up and shutting down the generating units as well as increasing and decreasing power generation. Fan, *et al.* [4] have proposed an efficient and practical approach for determining the feasible optimal solution of the ED problem, when some of the on-line units have prohibited operating zones. Wood [5] has proposed an efficient algorithm for the solution of a reserve constrained ED, which is the static optimization technique used at each interval.

Irisarri, *et al.* [6] have presented an approach to the ED problem that combines both time-separated constraints *(e.g.,* demand and network flow) and inter-temporal constraints (e.g., ramping) into a single optimization problem that can be solved efficiently by interior point methods. Su and Chiou [7] have presented a direct-computation Hopfield method for solving the ED problems of thermal generators. Lee, *et al.* [8] have developed two different methods (slope adjustment and bias adjustment methods) for ED problem, in order to speed up the convergence of the Hopfield neural network system. Liang and Glover [9] have presented the DP method for solving ED of a system of thermal generating units including transmission line losses. Roa-Sepulveda and Herrera [10] explains a improvement in the decision tree technique so that the numerical convergence of the overall technique improves. Roa-Sepulveda, *et al.* [11] explains a improvement in the decision tree technique by adding fuzzy logic to the unit limits and load. Aravindhababu and Nayar [12] presents a efficient method for on-line ED, which is based on the radial basis function (RBF) network that directly gives the optimal value of lambda for a given power demand. Moya [13] has proposed that deals with the composed problem of optimizing ED, fast spinning reserve and load shedding in order to withstand major sudden generation losses without collapsing by cascading effects. Granelli and Montagna [14] present a procedure for efficiently handling real power transmission constraints on branch flows and inter-area exchanges to supplement the classic ED formulation using dual quadratic programming.

Al-Sumait, *et al.* [15] have presented a approach based on a constrained pattern search algorithm to solve well-known power system ELD problem with valve-point effect. Walters and Shebleb [16] has proposed a genetics-based algorithm which is used to solve an ED problem for valve point discontinuities. Gaing [17] has proposed PSO algorithm to solving the ED considering the generator constraints. KumarSelva and Thanushkodi [18] have proposed a version of the classical PSO, to solve non-convex ED problems. Baskar and Mohan [19] have proposed to evolve simple and effective methods for the ELD problem with security constraints in thermal units, which are capable of obtaining economic scheduling for utility system. In the proposed PSO method, a new velocity strategy equation is formulated suitable for a large scale system and the features of constriction factor approach are also incorporated. Jayabarathi, *et al*. [20] have proposed different EP techniques for all kinds of ED problems. The three EP techniques considered here differ in the kind of mutation they use: Gaussian, Cauchy and combined Gaussian–Cauchy mutation. Noman and Iba [21] have presented DE algorithm for solving ELD problems in power systems. DE has proven to be effective in solving many real world constrained optimization problems in different domains. Wu, *et al*. [22] presents a multi-objective DE algorithm for environmental/economic power dispatch (EED) problem. The EED problem is formulated as a nonlinear constrained multi-objective problem with competing and non-commensurable objectives of fuel cost, emission and system loss.

Wang, *et al.* [23] have presented an efficient hybrid genetic algorithm (HGA) approach for solving the ED problem with valve-point effect. Coelho and Mariani [24] have proposed a approach for solving ELD problems with valve-point effect. The proposed method combines the DE algorithm with the generator of chaos sequences and SQP technique to optimize the performance of ED problems. The DE with chaos sequences is the global optimizer, and the SQP is used to fine-tune the DE run in a sequential manner. Bhattacharya and Chattopadhyay [25] presents a hybrid technique combining DE with biogeography-based optimization algorithm to solve both convex and non-convex-ELD problems of thermal power units considering transmission losses, and constraints such as ramp rate limits, valve-point loading and prohibited operating zones. Duvvuru and Swarup [26] have proposed a hybrid algorithm connecting interior point method and DE for solving ELD problem with valve point effect.

Dynamic economic dispatch is an extension of the conventional ED problem that takes into consideration the limits on the ramp rate of the generating units. Since DED needs to consider the internal coupling of the operation of power grid and units in each continuous time interval, there are more constraints and higher variable-dimensions and that makes it more difficult to find optimal solution than SED. Ross and Kim [27] have presented a set of procedures and algorithms for DED of generation units. Yorino *et al.* [28] have proposed a real-time DELD method to meet the general requirements for real-time use in a future power system, where load following capability is critically limited. Han, *et al.* [29] have presented examines the factors that affect the feasibility and optimality of solutions to the DED problem. It proposes two new solution methods. The first is guaranteed to find a feasible solution even when the load profile is non-monotonic. The second is an efficient technique for finding the optimal solution. Ferrero and Shahidehpur [30] have presented the effect of dynamic constraints on power transactions for DED problem in deregulated environments.

Jabr, *et al.* [31] presents a study of the homogeneous interior point method for DED problem that combines both independent blocks of constraints (generation demand balance, network flows) and coupling constraints (ramping) into a single optimization problem. Niimura and Yokoyama [32] have proposed to apply fuzzy set theory to decision-making in optimal generation dispatch for DED problem of thermal generating units. Travers and Kaye [33] have presented a DP method of solving the DED problem. Barcelo and Rastgoufard [34] have proposed an algorithm for solving the multi-stage DED (MDED) problem in real-time. The MDED problem is formulated by formally adding ramp rate constraints to the extended security constrained ED problem for all stages beyond the first stage.

Basu [35] has presented non-dominated sorting GA-II for dynamic economic emission dispatch problem (DEED). This problem is formulated as a nonlinear constrained multi-objective optimization problem. Basu [36] has proposed artificial immune system (AIS) based on the clonal selection principle for solving DED problem. This approach implements adaptive cloning, hyper-mutation, aging operator and tournament selection. Hemamalini and Simon [37] have proposed clonal selection based AIS algorithm is used to solve the DED problem for generating units with valve-point effect. Niknam and Golestaneh [38] have proposed an enhanced bee swarm optimization method to solve the DED problem of thermal units considering the valve-point effects, ramp-rate limits, and the transmission power losses. The bee swarm optimization algorithm unlike most of the population based algorithms employs different moving patterns to search the feasible solution space. This property makes an effective balance between exploration and exploitation. Different modifications in moving patterns of the bee swarm optimization method are proposed to search the feasible space more effectively. Balamurugan and Subramanian [39] have presented the DE approach to solve the DED problem, including valve-point effects. Peng, *et al.* [40] have proposed a novel bi-population chaotic DE algorithm for DED problem.

Victoire and Jeyakumar [41] have proposed a hybrid solution methodology integrating PSO algorithm with the SQP method for the reserve constrained DED problem of generating units considering the valve-point effects. The hybrid method incorporates the PSO algorithm as the main optimizer and SQP as the local optimizer to fine-tune the solution region whenever the PSO algorithm discovers a better solution region in the progress of its run. Attaviriyanupap, *et al*. [42] have proposed hybrid EP and SQP for DED problem.

DE is a population-based stochastic search technique that works in the general framework of evolution algorithms. The design principles of DE are simplicity, efficiency and use of real coding. It starts to explore the search space by randomly choosing the initial candidate solutions within the boundary. Then the algorithm tries to locate the global optimum solution for the problem by iterated refining of the population through reproduction and selection. Epitropakis, *et al.* [43] have proposed the paper in which random selection of parents during mutation is modified, by assigning to each individual a probability of selection that is inversely proportional to its distance from the mutated individual. Bhowmik, *et al.* [44] employs Lagrange's mean value theorem of differential Calculus to design a new strategy for the selection of parameter vectors in the DE algorithm.

Chiou, *et al.* [45] presents an ant direction hybrid DE with integer programming which is effective and efficient for solving large capacitor placement problems in distribution systems. Chiou, *et al.* [46] have presented an effective method variable scaling hybrid DE for solving the network reconfiguration for power loss reduction and voltage profit enhancement of distribution systems. Liang, *et al.* [47] have proposed a method based on the cooperative co-evolutionary architecture and the voltage-var sensitivity- based power system decomposition technique to overcome the requirement of relatively large population to avoid premature convergence incorporated with DE. Cai, *et al.* [48] have presented a robust and efficient method for solving transient stability constrained optimal power flow problems based on DE, which is a new branch of evolutionary algorithms with strong ability in searching global optimal solutions of highly nonlinear and non-convex problems.

1.3 Author's Contribution

The objective of the DELD is to schedule power generation for the committed units over a time horizon, satisfying the unit and ramp-rate constraints and DE algorithm is implemented to solve the scheduling problem. Results of the proposed technique are compared with the results obtained from various optimization methods.

1.4 Organization of the Thesis

Thesis titled as "*Dynamic economic load dispatch using differential evolution*" is divided into six chapters. Chapter two describes the formulation of DELD problem. Chapter three deals with the explanation of DE technique and its algorithm. Chapter four presents the solution approach to the DELD using DE. Chapter five covers the discussion pertaining to results and chapters six summarize the conclusions and scope for further work.

CHAPTER 2 DYNAMIC ECONOMIC LOAD DISPATCH

2.1 Introduction

Power utilities are expected to generate their power at minimum cost. The generated power has to meet the load demand and transmission losses. This implies that the dispatch at the true minimum cost requires that we take the network losses into account. Also, for the secure operation of the power system, the generators must be dispatched so that the transmission capacity limits are not exceeded. The transmission limits can be determined from line thermal considerations or from a full stability study. Moreover, the generators' ramp rate limits the change in power output between consecutive intervals [10]. Dynamic Economic Dispatch is a method to schedule the online generator outputs with the predicted load demands over a certain period of time so as to operate an electric power system most economically. It is a dynamic optimization problem taking into account the constraints imposed on system operation by generator ramping rate limits. DED is not only the most accurate formulation of the ED problem but also the most difficult to solve because of its large dimensionality. Normally, it is solved by dividing the entire dispatch period into a number of small time intervals, and then a SED has been employed to solve the problem in each interval [13]. Since DED was introduced, several methods have been used to solve this problem. However, all of those methods may not be able to provide an optimal solution and usually getting stuck at a local optimal. Recently, stochastic optimization techniques such as GA [16], AIS [36-37], enhanced bee swarm optimization algorithm [38],EP [42] and DE [43-44] have been given much attention by many researchers due to their ability to seek for the near global optimal solution.

2.2 Problem Formulation

The dynamic economic dispatch is aimed to minimize the total fuel cost as much as possible by determining the optimal combinations of output of all generating units over the dispatch periods, while satisfying all kinds of physical and operational constraints. Generally, the objective function and associated constraints of the DED problem can be formulated as follows.

2.2.1 Objective Function

The objective function of DED problem minimizes the following total fuel cost of committed units.

$$\min F\left(P_{j,t}\right) = \sum_{t=0}^{T}\sum_{j=0}^{NG}\left[f\left(P_{j,t}\right)\right] \tag{2.1}$$

where

F is the total fuel cost

$P_{i,t}$ is the output of the ith unit at the tth time interval

f_i is the cost function of the ith unit

NG is the number of generating units

T is the number of intervals over the dispatch horizon

Traditionally, the production cost function of each unit is described as a quadratic function, which can be represented as follows:

$$f\left(P_{j,t}\right) = \left(a_j + b_j P_{j,t} + c_j P_{j,t}^2\right) + \left| d_j Sin(e_j(P_j^{\min} - P_{j,t}))\right| \tag{2.2}$$

where

a_j, b_j, c_j, d_j and e_j are cost coefficients of the jth unit.

2.2.2 Constraint

There are three types of constraints on which given problem depend. First one is real power balance constraints which look after that demand plus transmission losses are equal to the total power generation. Second one is the inequality constraints which check the maximum and minimum limits of power generations. Third type constraint discusses about ramp rate limits.

Real power balance constraint

The total real power generation must balance the predicted power demand plus the real power losses in the transmission lines, at each time interval over the scheduling horizon.

$$\sum_{j=1}^{NG} P_{j,t} - \left(P_{D,t} + P_{L,t}\right) = 0 \qquad (j = 1,2,\ldots,NG;\ t = 1,2,\ldots,T) \tag{2.3}$$

where

$P_{D,t}$ is the load demand at the tth time interval.

$P_{L,t}$ is the power loss at the t^{th} time interval, which can be calculated by using the B loss coefficients matrix in the quadratic form as follows:

$$P_{L,t} = \sum_{i=1}^{NG}\sum_{j=1}^{NG} P_{i,t} B_{ij} P_{j,t} + \sum_{i=1}^{NG} B_{oi} P_{i,t} + B_{oo} \qquad (j = 1,2,....NG; t = 1,2,...,T; i = 1,2,...,L) \qquad (2.4)$$

where

B_{ij}, B_{0i} and B_{00} are the power loss coefficients.

Output Capacity limit

The elements of P(j,t,i) may violate constraint Equations. This violation is corrected by fixing them either by lower or upper limit as described below:

$$P_j^{min} \le P_{j,t} \le P_j^{max} \qquad (j = 1,2,..., NG; t = 1,2,...,T) \qquad (2.5)$$

where

P_j^{min} is the minimum output limits of the j^{th} units

P_j^{max} is the maximum output limits of the j^{th} units.

Generating unit ramp rate limit

Ramp rates are the maximum rates specified for each unit at which the power output of a unit can be increased (ramp up rate) or decreased (ramp down rate) in a time interval. Violation of generation ramp rates will shorten the life of the rotor and therefore has to be satisfied in a practical system operation where the generation changes with demand.

$$P_{j,t} - P_{j,t-1} \le UR_j \text{ if output increases} \qquad (2.6)$$

$$P_{j,t-1} - P_{j,t} \le DR_j \text{ if output decreases} (j = 1,2,..., NG;\ t = 1,2,...,T) \qquad (2.7)$$

where

$P_{j,t}$ is the power output of j^{th} unit at t^{th} time

$P_{j,t-1}$ is the power output of j^{th} unit at $(t-1)^{th}$ time

UR_j is the maximum output ramp up rate limit of the j^{th} unit

DR_j is maximum output ramp down rate limit of the j^{th} unit.

CHAPTER 3 DIFFERENTIAL EVOLUTION

3.1 Introduction

Differential evolution algorithm is a simple and powerful population-based stochastic optimization algorithm, which is originally motivated by the mechanisms of natural selection. Since it does not require the derivative information, DE is very effective for solving optimization problems with non-smooth and non-convex characteristics. This technique combines simple arithmetic operator with classic evolutionary operators, such as mutation, crossover and selection. The key idea behind DE is a scheme for generating trial vectors. Mutation is used to generate a mutant vector by adding differential vectors obtained from the difference of several randomly chosen parameter vectors to the parent vector. After that, a trial vector is produced by a crossover through recombining the obtained mutant vector with the target vector. Finally, according to the fitness value, selection determines which of the vectors will be chosen for the next generation by implementing one-to-one competition between the new generated trial vectors and their corresponding parents.

3.2 Initialization

The population is initialized by randomly generating individuals within the boundary constraints,

$$X_{ji}^{o} = X_{j}^{\min} + rand() \times \left(X_{j}^{\max} - X_{j}^{\min}\right) \qquad (j = 1,2,...,NG; i = 1,2,...,L) \tag{3.1}$$

where

X_{ji}^{0} is the initialized j^{th} decision variable of i^{th} population set

rand() are random values uniformly in the interval [0,1]

L is the size of the population

X_j^{min} is the lower bound of the j^{th} decision variable

X_j^{max} is the upper bound of the j^{th} decision variable.

3.3 Mutation

'Mutation' occupies quite an important role in the reproduction cycle. The mutation operation creates mutant vectors X'^{k}_{i} by perturbing a randomly selected vector X^k_a with the difference of two other randomly selected vectors X^k_b and X^k_c at kth iteration as per following equation.

$$X_i^{`k} = X_a^k + F \times (X_b^k + X_c^k) \qquad (i = 1,2,...,L) \tag{3.2}$$

where

$X^{`k}_i$ is the newly generated i^{th} population set after performing mutation operation at k^{th} iteration

X^k_a, X^k_b and X^k_c are randomly chosen vectors at k^{th} iteration and a ≠ b ≠ c ≠ i

F is a scaling factor

3.4 Crossover

Crossover represents a typical case of a 'genes' exchange. The parent vector is mixed with the mutated vector to create a trial vector, according to the following equation;

$$X_{ji}^{``k} = \begin{Bmatrix} X_{ji}^{`k} & if\ rand\ j \le CR\, or\ j = q \\ X_{ji}^{k} & otherwise \end{Bmatrix} \quad (j = 1,2,...,NG; i = 1,2,...,L) \tag{3.3}$$

where

X_{ji}^k is the j^{th} individual of i^{th} target vector at k^{th} iteration ;

$X`_{ji}^k$ is the j^{th} individual of i^{th} mutant vector at k^{th} iteration;

$X``_{ji}^k$ is the j^{th} individual of i^{th} trial vector at k^{th} iteration;

q is a randomly chosen index;

CR is the Crossover constant.

3.5 Selection

Selection procedure is used among the set of trial vector and the updated target vector to choose the best. Each solution in the population has the same chance of being selected as parents. Selection is realized by comparing the objective function values of target vector and trial vector. For minimization problem, if the trial vector has better value of the objective function, then it replaces the updated one as per per given equation:

$$X_i^{k+1} = \begin{Bmatrix} X_i^{``k} & if\ f(X_i^{``k}) \le f(X_i^k) \\ X_i^k & \end{Bmatrix} \qquad (i = 1,2,...,L) \tag{3.4}$$

where

X_i^{k+1} is the i^{th} population set obtained after selection operation at the end of k^{th} iteration, to be used as parent population set in next iteration $(k + 1)^{th}$.

CHAPTER 4 DYNAMIC ECONOMIC LOAD DISPATCH USING DIFFERENTIAL EVOLUTION

4.1 Introduction

The process of the DE algorithm for solving DED problem can be summarized as follows. The objective optimization problem is defined as

$$Min\,F(P_{j,t}) = \sum_{j}^{NG} (a_j P_{j,t}^2 + b_j P_{j,t} + c_j + \left| d_j Sin(e_j (P_j^{\min} - P_{j,t})) \right|) \quad (4.1)$$

$$Minimum\,[F(P_{j,t})]$$

Subjected to

$$\sum_{j}^{NG} P_{j,t} - (P_{D,t} - P_{L,t}) = 0 \quad (4.2)$$

$$P_j^{\min} \le P_{j,t} \le P_j^{\max} \quad (j = 1,2,...,NG; t = 1,2,...,T) \quad (4.3)$$

where

$F(P_{j,t})$ is the objective to be minimized over the set of admissible decision vector $P_{j,t}$

NG is the number of generators

a_j,b_j,c_j,d_j and e_j are the cost coefficients of j^{th} unit.

$P_{D,t}$ is the power demand at t^{th} time

$P_{L,t}$ is the transmission losses at t^{th} time which approximated in terms of B-coefficients .

The transmission losses are defined as

$$P_L = B_{00} + \sum_{j}^{NG} B_{j0} P_{j,t} + \sum_{m}^{NG} \sum_{j}^{NG} P_{m,t} B_{mj} P_{j,t} \quad MW \quad (4.4)$$

where

B_{00}, B_{j0} and B_{mj} are the transmission loss coefficient.

4.2 DYNAMIC ECONOMIC LOAD DISPATCH USING DE

The output power generation of each unit in DED problem is determined with respect to predicted load demand over a period satisfying the unit and system constraints and ramp-rate constraint. Penalty parameter is used to satisfy the real power constraint. Since DED was introduced, several methods have been used to solve this problem. DE is a population-based stochastic search technique that works in the general framework of evolution algorithms mainly based on mutation operator. The detailed implementation of the DE algorithm to find an optimal solution for the DED problem is given below:

4.2.1 INTILIZATION

The structure of an individual for DED problem is composed of a set of generation power decision variables for each unit in over the scheduling horizon generated by random number, which lies between its maximum and minimum value respectively. Expression of power is as follows:

$$P(j,t,i) = P_j^{\min} + rand()X(P_j^{\max} - P_j^{\min}) \quad (j = 1,2,...,NG; t = 1,2,...,T;\ i = 1,2,...,L)$$

(4.5) where

P(j,t,i) is power generation of j^{th} unit at time t for i^{th} population.

$P_j^{\min}$ is lower generation limits for j^{th} unit

$P_j^{\max}$ is upper generation limits for j^{th} unit

rand () is uniform distributed random number between 0 and 1

L is population size

T is time period for scheduling

NG is number of generating units

Since the decision variables of the DED problem are real power generations, they are used to form the swarm. The set of real power output of all the generators is represented as the position of the particle in the swarm. For a system with NG generators, the particle is represented as a vector of length NG. A matrix representation of a particle with population is as

$$P = \begin{bmatrix} \begin{bmatrix} P(1,1,1) \; P(2,1,1)\ldots\ldots\ldots\ldots P(NG,1,1) \\ P(1,2,1) \; P(2,2,1)\ldots\ldots\ldots\ldots P(NG,2,1) \\ P(1,T,1) \; P(2,T,1)\ldots\ldots\ldots\ldots P(NG,T,1) \end{bmatrix} \\ \begin{bmatrix} P(1,2,1) \; P(2,1,2)\ldots\ldots\ldots\ldots P(NG,1,2) \\ P(1,2,2) \; P(2,2,2)\ldots\ldots\ldots\ldots P(NG,2,2) \\ P(1,T,2) \; P(2,T,2)\ldots\ldots\ldots\ldots P(NG,T,2) \end{bmatrix} \\ \begin{bmatrix} P(1,1,L) \; P(2,1,L)\ldots\ldots\ldots\ldots P(NG,1,L) \\ P(1,1,L) \; P(2,1,L)\ldots\ldots\ldots\ldots P(NG,1,L) \\ .P(1,T,L) \; P(2,T,L)\ldots\ldots\ldots\ldots P(NG,T,L) \end{bmatrix} \end{bmatrix} \tag{4.6}$$

4.2.2 COST FUNCTION

The objective optimization problem is defined as:

$$Min\,F(P_{j,t}) = \sum_{j}^{NG} (a_j P_{j,t}^2 + b_j P_{j,t} + c_j + \left| d_j Sin(e_j (P_j^{\min} - P_{j,t})) \right|) \tag{4.7}$$

where

a_j,b_j,c_j,d_j and e_j are the cost coefficients of j^{th} unit.

The transmission losses are defined as

$$P_L = B_{00} + \sum_{j}^{NG} B_{j0} P_{j,t} + \sum_{m}^{NG} \sum_{j}^{NG} P_{m,t} B_{mj} P_{j,t} \tag{4.8}$$

where

B_{00}, B_{j0} and B_{mj} are the transmission loss coefficient.

Subjected to:

Equality Constraint:

The total generating power has to be equal to the sum of load demand and transmission losses.

$$\sum_{j}^{NG} P_{j,t} - (P_{D,t} - P_{L,t}) = 0 \tag{4.9}$$

where

$P_{j,t}$ is the power generated of j^{th} unit at t^{th} interval.

$P_{D,t}$ is the power demand at t^{th} interval.

$P_{L,t}$ is the transmission losses at t^{th} interval.

Inequality Constraints:

$$P_j^{\min} \le P_{j,t} \le P_j^{\max} \qquad (j = 1,2,...,NG; t = 1,2,....,T)$$

(4.10) where

$P_{j,t}$ = power generation of jth unit at time t.

$P_j^{\min}$ = lower generation limits for jth unit.

$P_j^{\max}$ = upper generation limits for jth unit.

The elements of P(i,k,j) may violate constraint Eq. (4.5). This violation is corrected by fixing them either by lower or upper limit as described below:

$$P(j,t,i) = \begin{cases} P_j^{\min}; P_{j,t,i} < P_j^{\min} \\ P_{j,t,i} \; ; P_j^{\max} \le P_{j,t,i} \le P_j^{\min} \;\; (j = 1,2,...,NG; t = 1,2,...,T, i = 1,2,...,L) \\ P_j^{\max}; \; P_{j,t,i} > P_j^{\max} \end{cases} \tag{4.11}$$

Generating unit ramp rate limits:

Ramp rates are the maximum rates specified for each unit at which the power output of a unit can be increased (ramp up rate) or decreased (ramp down rate) in a time interval. Violation of generation ramp rates will shorten the life of the rotor and therefore has to be satisfied in a practical system operation where the generation changes with demand.

$P_{j,t} - P_{j,t-1} \le UR_j$ if output increases (4.12)

$P_{j,t-1} - P_{j,t} \le DR_j$ if output decreases $(j = 1,2,..., NG; \; t = 1,2,...,T)$ (4.13)

where

$P_{j,t}$ is the power output of jth unit at tth time interval

$P_{j,t-1}$ is the power output of jth unit at (t-1)th time interval

UR_j is the maximum output ramp up rate limit of the jth unit

DR_j is maximum output ramp down rate limit of the jth unit.

4.2.3 MUTATION OPERATION

Mutation is an operation that adds a vector differential to a population vector of individuals. The perturbed individuals are generated by mutation process as described below.

$$V(i,k,j) = P(i,k,j) + F \times (P(q_1,k,j) - P(q_2,k,j)) \tag{4.14}$$

4.2.4 CROSSOVER OPERATION

Following the mutation operation, crossover is applied to the population. The perturbed individual and the present individual are chosen by a binomial distribution to perform the crossover operation to generate the offspring and it is given as:

$$U(j,t,i) = P(j,t,i) \times (1 - CR) + V(j,t,i) \times CR \tag{4.15}$$

The crossover factor (CR) is taken from the interval of [0,1].

4.2.5 EVALUATION OF EACH AGENT

In order to satisfy the power balance constraint, error is calculated using the power balance equation, which is given by

$$E = \sum_{j}^{NG} P_{j,t,i} - (P_{D,t} + P_{L,t}) \quad (j = 1,2,...,NG; t = 1,2,...,T; i = 1,2,...,L)$$

(4.16)

Each individual in the population is evaluated using the fitness function of the problem to minimize the fuel-cost function. The power balance constraint is augmented with the objective to form a generalized fitness function FIT, given as

$$FIT = \sum_{j}^{NG} F(P_{j,t,i}) + PF(E)^2 \quad (j = 1,2,...,NG;\ t = 1,2,...,T; i = 1,2,...L) \tag{4.17}$$

where PF is the penalty parameter. The penalty term reflects the violation of the equality constraint and assigns a high cost of penalty function to a candidate point far from the feasible region.

4.2.6 ESTIMATION AND SELECTION

The selection operation selects according to the fitness value of the population/parent vector and its corresponding trial/target vector.

$$P_{j,t,i} = \begin{Bmatrix} P_{j,t,i} & if\ F(P_{j,t,i}) \le F(U_{j,t,i}) \\ U_{j,t,i} & otherwise \end{Bmatrix}$$

(4.18)

Using above equation, the cost of each trial vector $U_{j,t,i}$ is compared with that of its parent target vector $P_{j,t,i}$. If the cost F, of the parent vector is lower than that of trial vector, then the parent vector is allowed to advance to the next generation, otherwise, the parent vector is replaced by the trial vector in the next generation. The mutation, crossover and selection are repeated upto specified number of iteration to get optimal solution.

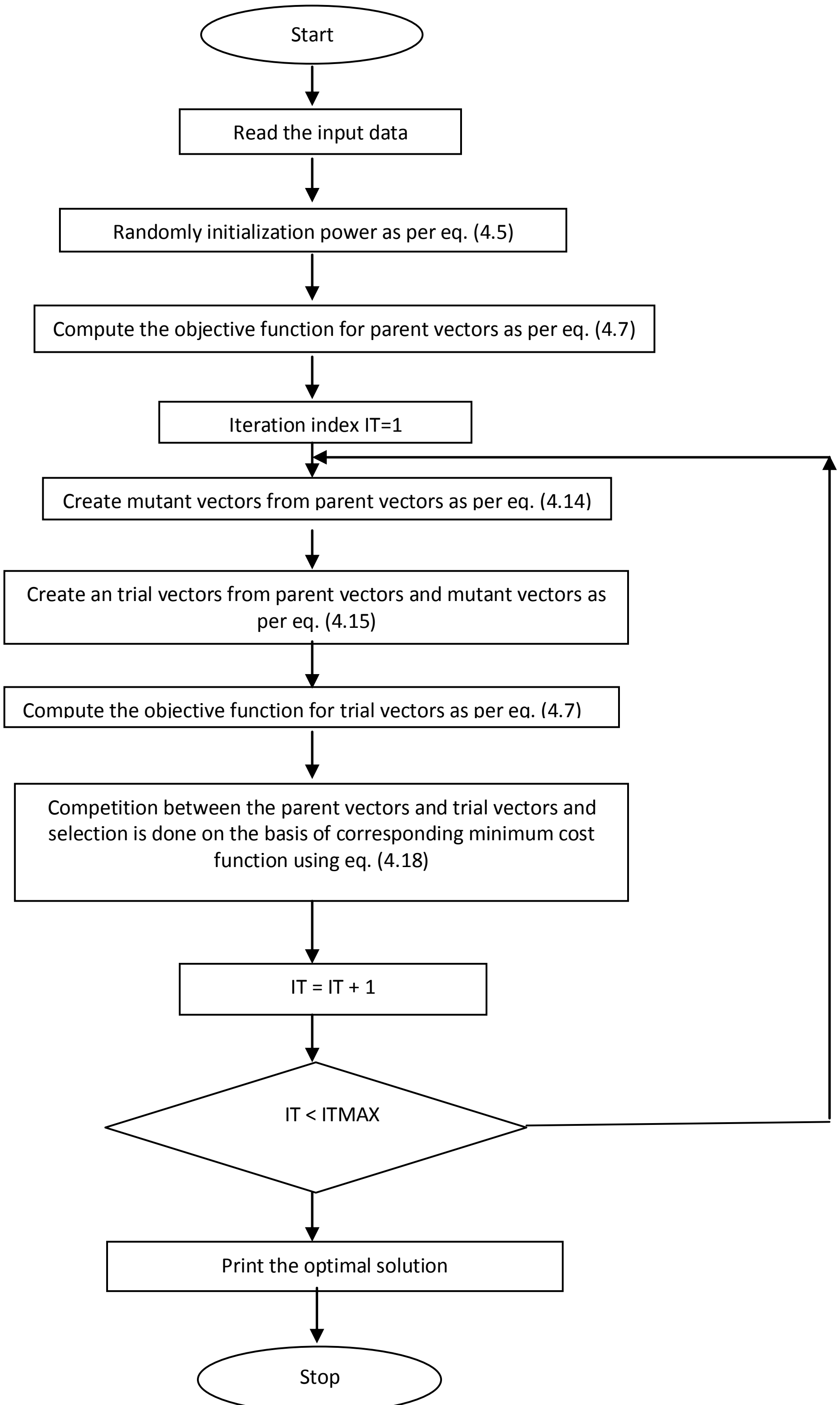

Fig 4.1 Flow chart for dynamic economic load dispatch using differential evolution

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Introduction

In this research work, the results have been obtained from the developed algorithm for dynamic economic load dispatch on DE, which has been discussed in Chapter-4. The developed algorithm has been tested on 10 generating units systems considering (1) with valve point loading and (2) without valve point loading. Input data is also given in APPENDIX- I . As explained in Chapter-4, the power dispatch problem has been formed on basis of DED which is formulated with objective of minimizing fuel cost. Keeping the above, the following cases have been studied- Case Study 1: DELD for 10 generating units (without valve point loading). Case Study 2: DELD for 10 generating units (with valve point loading).

5.1.1 Case Study 1: DELD for 10 generating units (without valve point loading).

The input parameters are taken from [35]. The cost and powers are as given in Table 5.1:

Table 5.1: Hourly generation (MW) schedule and cost (X 10^6 \$)

Hour	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	Cost
1	150.00	135.00	137.77	151.08	133.98	130.71	85.23	92.29	25.65	13.69	2.4268
2	150.00	135.00	136.59	103.35	129.98	147.25	115.87	97.29	70.01	47.02	
3	150.00	135.00	180.67	222.88	189.055	138.55	115.26	89.44	41.35	24.24	
4	150.00	135.00	191.37	216.39	234.74	157.14	123.88	120.00	65.47	47.48	
5	150.00	135.00	246.57	212.98	243.00	160.00	130.00	120.00	67.44	54.40	
6	150.00	135.00	323.60	297.46	243.00	160.00	130.00	120.00	79.98	54.99	
7	150.00	176.95	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
8	181.55	224.85	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
9	247.39	319.18	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
10	291.55	382.06	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
11	329.67	436.24	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
12	349.82	464.69	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
13	314.38	414.09	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
14	247.45	319.11	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
15	181.55	224.85	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
16	150.00	135.00	288.84	244.00	243.00	160.00	130.00	120.00	73.59	53.14	
17	150.00	135.00	254.54	232.66	235.44	138.86	130.00	120.00	69.82	53.20	
18	150.00	135.00	340.00	271.12	243.00	160.00	130.00	120.00	73.49	53.50	
19	181.55	224.85	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
20	268.95	349.93	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
21	247.46	319.11	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
22	150.00	135.00	340.00	271.12	243.00	160.00	130.00	120.00	73.49	53.50	
23	150.00	149.02	183.13	204.12	199.61	151.49	120.75	106.68	66.29	46.76	
24	150.00	149.02	199.42	191.15	152.11	136.33	89.60	95.89	29.69	16.13	

5.1.2 Case Study 2: DELD for 10 generating units (with valve point loading).

The input parameters are taken from [35]. The cost and powers are as given in table 5.2:

Table 5.2: Hourly generation (MW) schedule and cost (X 10^6 $)

Hour	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	Cost
1	150.00	135.00	139.98	163.24	128.14	125.59	83.65	90.46	25.57	13.79	2.4675
2	150.00	144.99	176.33	173.33	128.31	140.25	90.65	98.40	20.00	10.00	
3	150.00	135.00	185.20	180.83	183.01	138.57	117.75	85.31	67.38	43.42	
4	150.00	135.00	217.64	241.05	222.60	127.82	112.89	119.92	165.17	49.59	
5	150.00	135.00	289.40	241.29	222.60	124.16	124.55	120.00	67.52	45.29	
6	150.00	135.00	340.00	274.67	243.00	160.00	130.00	120.00	80.00	43.42	
7	150.00	188.60	340.00	300.00	243.00	160.00	130.00	120.00	80.00	43.42	
8	184.13	222.27	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
9	257.01	309.53	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
10	276.84	396.80	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
11	369.06	396.80	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
12	379.87	434.56	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
13	303.25	425.27	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
14	257.01	309.53	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
15	184.13	222.27	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
16	150.00	135.00	297.40	256.50	225.26	160.00	130.00	120.00	80.00	43.42	
17	150.00	135.00	289.40	241.29	222.60	124.16	124.55	120.00	67.52	45.29	
18	150.00	135.00	340.00	274.67	243.00	160.00	130.00	120.00	80.00	43.42	
19	184.13	222.27	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
20	226.62	392.51	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
21	257.01	309.53	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00	
22	150.00	135.00	340.00	274.67	243.00	160.00	130.00	120.00	80.00	43.42	
23	150.00	135.00	267.08	224.67	203.76	122.37	85.51	102.68	45.79	27.36	
24	150.96	142.42	187.21	193.37	161.94	135.06	96.06	94.16	30.31	17.78	

Table 5.3: Comparison with techniques shows the effectiveness of applied method

Methods	Cost (X 10^6 $)
DE (without valve point loading)	2.4268*
DE (with valve point loading)	2.4675*
RCGA	2.5168
AIS	2.5197
PSO	2.5722

*Ramp rate limits are not considered in this problem

Real Coded Genetic Algorithm-RCGA, Artificial Immune System -AIS

From Table 5.3, it clearly sees that DE method yields better results than RCGA, AIS and PSO while satisfying equality and inequality constraints.

CHAPTER 6 CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion

Dynamic economic load dispatch problem has been solved for 10 generating units system considering without valve point loading and with valve point loading conditions using DE algorithm.

Differential Evolution algorithm is a heuristic approach mainly having three advantages; finding the true global minimum of a multi modal search space regardless of the initial parameter values, fast convergence, and using a few control parameters. DE algorithm is a population based algorithm like genetic algorithms using the similar operators; crossover, mutation and selection. The results clearly show the effectiveness of the method in solving DED problem. The results obtained are compared with those in the literature. The algorithm outperforms the other methods and is able to reach the solutions that were not reached using the other techniques.

6.2 Scope For Future Work

The scope of work after studying Dynamic Economic Dispatch using DE is identified as:

- This problem can be applied to Practical Systems.
- Extend the problem by incorporating more than objectives like emissions etc.

APPENDIX

APPEXDIX-A

Table A.1: Input data for 10 generating units:

Unit	Pmin (MW)	Pmax (MW)	a_i \$/(MW)^{2}h	b_i \$/MWh	c_i \$/h	d_i \$/h	e_i rad/MW	UR_i (MW/h)	DR_i (MW/h)
1	150	470	0.1524	38.5397	786.7988	450	0.041	80	80
2	135	470	0.1058	46.1591	451.3251	600	0.036	80	80
3	73	340	0.0280	40.3965	1049.9977	320	0.028	80	80
4	60	300	0.0354	38.3055	1243.5311	260	0.052	50	50
5	73	243	0.0211	36.3278	1658.5696	280	0.063	50	50
6	57	160	0.0179	38.2704	1356.6592	310	0.048	50	50
7	20	130	0.0121	36.5104	1450.7045	300	0.086	30	30
8	47	120	0.0121	36.5104	1450.7045	340	0.082	30	30
9	20	80	0.1090	39.5804	1455.6056	270	0.098	30	30
10	10	55	0.1295	40.5407	1469.4026	380	0.094	30	30

Table A.2: B-coefficients for 10-generating units:

0.00049	0.00014	0.00015	0.00015	0.00016	0.00017	0.00017	0.00018	0.00019	0.00020
0.00014	0.00045	0.00016	0.00016	0.00017	0.00015	0.00015	0.00016	0.00018	0.00018
0.00015	0.00016	0.00039	0.00010	0.00012	0.00012	0.00014	0.00014	0.00016	0.00016
0.00015	0.00016	0.00010	0.00040	0.00014	0.00010	0.00011	0.00012	0.00014	0.00015
0.00016	0.00017	0.00012	0.00014	0.00035	0.00011	0.00013	0.00013	0.00015	0.00016
0.00017	0.00015	0.00012	0.00010	0.00011	0.00036	0.00012	0.00012	0.00014	0.00015
0.00017	0.0001	0.00014	0.00011	0.00013	0.00012	0.00038	0.00016	0.00016	0.00018
0.00018	0.00016	0.00014	0.00012	0.00013	0.00012	0.00016	0.00040	0.00015	0.00016
0.00019	0.00018	0.00016	0.00014	0.00015	0.00014	0.00016	0.00015	0.00042	0.00019
0.00020	0.00018	0.00016	0.00015	0.00016	0.00015	0.00018	0.00016	0.00019	0.00044

Table A.3: LOAD DEMANDS

Hour	P_D(MW)	Hour	P_D(MW)	Hour	P_D(MW)
1	1036	9	1924	17	1480
2	1110	10	2022	18	1628
3	1258	11	2106	19	1776
4	1406	12	2150	20	1972
5	1480	13	2072	21	1924
6	1628	14	1924	22	1628
7	1702	15	1776	23	1332
8	1776	16	1554	24	1184

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