

THERMAL UNIT COMMITMENT USING EVOLUTIONARY PROGRAMMING

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CERTIFICATE

I hereby certify that the work which is being presented in Thesis entitled, "**Thermal Unit Commitment Using Evolutionary Programming**", 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. Nitin Narang, Assistant Professor (EIED)**. The matter presented in this thesis has not been submitted for the award of any other degree to any other university.

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ABSTRACT

Thermal unit commitment problem (TUCP) is defined as committing an enough units to supply a power to network or a system with respect to load demand optimally. It is mixed-integer non-linear optimization problem subjected to various constraints. Various conventional and random search techniques are applied for the solution of TUCP.

In the thesis work, three types of evolutionary programming (EP) techniques i.e. classical evolutionary programming, fast evolutionary programming and improved fast evolutionary programming are employed for the solution of TUCP as EP has more capability of converging to global optimal solution and tested on two unit commitment problem. Results obtained are compared with the results reported in the literature.

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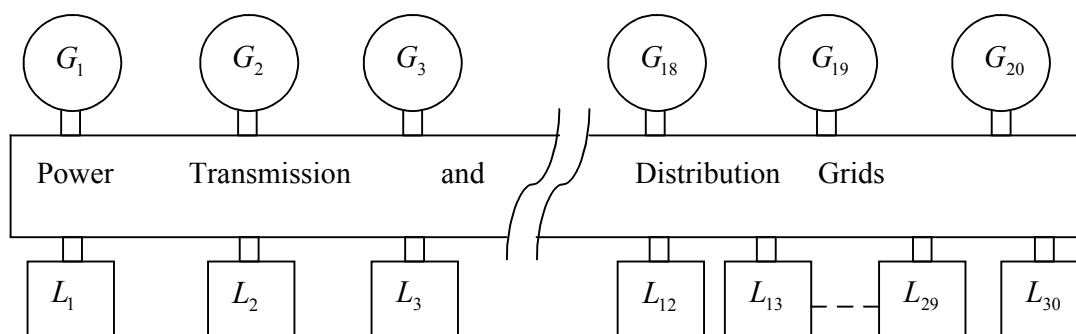
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CHAPTER 1

INTRODUCTION

1.1 Introduction

In power industry fuel expenses constitute a significant part of overall generation cost. So it's being necessary put some limitation on the usage of fuel for generating power. This can be achieved by proper scheduling of generating of units termed as unit commitment (UC). Therefore unit commitment is an essential step in scheduling and dispatching of electric power [1]. So UC is forward positive step to make a balance between generating power and load demand. So broadly UC is defined as committing an enough units to supply a power to network or a system with respect to load demand. Consider a simple power system coupled to generating station or units at one end and consumer end or load end on the other end as shown in figure (1.1).



$G_1 - G_{20}$ -- Generators

Figure 1.1 A Simple Power System

$L_1 - L_{30}$ -- Load

It means that power system operation is continuously varying with respect to the consumers demand. The demand varies between weekdays and weekends and also between peak and off-peak hours. So therefore it is not economical to run all the generating units all the time i.e. keeping them online all the time as it gives high impact to economics [2]. So UC provides a proper coordination between generating power and its demand. Ultimately it's been concluded that load demand and power reserve requirement are considered as global constraints and rest all the operating characteristics are the local constraints. It means that unit commitment is time dependent problem. So therefore UC is the problem of scheduling of the generating units to keep online or offline as per the demand of electricity but subjected to various constraints. Various optimization techniques are applied to solve this problem deterministic techniques branch and bound method (BABM), priority list method (PLM) and

dynamic programming (DP), lagrangian relaxation method (LRM) [3-4]. Out of these PLM, DP and LRM techniques are mostly used in power plants to solve unit commitment problem. But having a drawback of being more computational and expensive as the optimization problem grown in both dimensionality and complexity [5]. Advancement in computation and the searching for better results for complex optimization problems leads to the development of random search techniques like evolutionary programming (EP), ant colony search method (ACSM), particle swarm optimization (PSO), genetic algorithm (GA) and simulated annealing (SA) [6]. Evolutionary programming method has convergence rate to find the global optimum solution for optimization problems is much better as it than earlier optimization techniques. Moreover it also provides fast and more accurate results as close to conventional methods in a reasonable time [7]. So it can be easily implemented to practical problems.

1.2 Literature Review

In Electrical power system unit commitment is non linear mixed integer optimization problem of deciding that which unit should be running to satisfy a demand of electricity requirement [8]. At one extreme nuclear power plants can provide electricity at low incremental cost for additional megawatt hour of energy but it has high start-up cost as it is once shutdown it will take a while to bring back it to a full power. Hydro power plants have high capital cost but low operating cost. So therefore it is optimum to make the proper utilization of optimum mix of generation unit to generate electricity but taking into consideration the local as well as global constraints [9]. Therefore UC is the problem of determining the schedule of the generating units to keep online or offline as per the demand of electricity but subjected to the device as well as the constraints. Unit commitment problem (UCP) resolved by lot of techniques and number of papers were presented by various researchers pertaining the solution to UCP. Happ, *et al.* [10] presents a approach of sub optimizer and optimizer for obtaining the online optimal solution for UCP and require less computation time with satisfaction of operating constraints. Cohen and Yoshimura [11] presented a technique of branch and bound to find the feasible optimal solution to UCP with decision variables as start, stop times and generation level of the generating units and implemented without the incorporation of priority ordering criteria for the generating units. Snyder, *et al.* [12] suggested dynamic programming approach to UCP with incorporating of special feature of controlling the optimization problem size and provides an economic allocation of fuel cost to generating units. Huang, *et al.* [13] proposed a combination of logic

programming with operating constraints satisfaction and branch bound technique to provide a flexible and efficient approach to UCP. Chowdhury and Billinton [14] develops a probabilistic approach involving system reliability and reserve requirement evaluation as two risk criteria's for the feasible solution of UCP for continually varying load demand. Bender decomposition method for obtaining the feasible optimal solution to UCP and reactive power and voltage constraints for confirmed convergence to optimality discussed by Ma and Shahidehpour [15]. Dillon, *et al.* [16] provides the method for determining the optimum generating schedule by incorporating some alternations in branch and bound method for integer programming approach and considering satisfaction of power reserve constraint. Unit commitment problem can be solved by linear programming approach (LP) [17-18]. Gray and Sekar [17] discussed a unified approach of LP with direct current network model (DCNM) for solving UCP and considering power security constraint. Tight description of feasible generating schedules for solving UCP with LP considering ramp constraint proposed by Ostrowski, *et al.* [18]. Chang, *et al.* [19] presented a mixed integer linear programming (MILP) for solution to UCP of a simple combined cycle generating model prevailing all the operating constraints satisfaction.

Short term UCP leads to feasible optimum solution considering satisfaction of all operating constraints using PLM approach suggested by Keong and Teshome [20]. A solution to UCP considering the satisfaction of all the operating constraints using LRM are discussed [21-28]. Virmani, *et al.* [21] provides an LRM approach to most feasible optimize solution to UCP and discussed LRM implementation aspects to realistic UCP. A transmission constrained UCP of DCNM leads to the optimal solution using LRM Tseng, *et al.* [22]. Bertsekas, *et al.* [23] and Merlin and Sandrin [24] provides a reliable optimal solution to large scale UCP within the realistic time constraints by LRM implementation. A three phase i.e. maximized and find optimal solution to UCP and economic load dispatch (ELD) using LRM presented by Zhuang and Giliana [25]. A hydro-thermal scheduling can obtain by using LRM with combination of BABM to relax the lagrangian multiplier proposed by Ahmed, *et al.* [26]. Nieva and Guillen [27] discussed the LRM for making the search area more confined leads to feasible optimal optimal solution to UCP along with implementation of DP and take into consideration of the satisfaction of all the operating constraints like minimum-up, down time, ramp rate. Baldick [28] suggest a lagrangian reduction methof for the solution to UCP prevailing the satisfaction of voltage and crew constraint. Mokhtari *et al.* [29] and Salam *et al.* [30] presented the expert system developed to assist the power system operator to schedule properly the units in respect to input information from operator or proper adjustment

of all the inputs to the generating units. A solution approach to UCP of a large scale generating system having varying load demand achieved by stochastic technique along with combination of LRM and DP has been discussed by Takriti *et al.* [31].

In previous research papers, different techniques have been suggested like DP, LRM, LP, MILP, PLM and BABM are reliable and results to local optimal solution but having problem of large calculation and more time for calculation as optimization problem increase dimensionally [32-33]. Different random search has been developed for the solution to UCP like EP, GA and ACSM, improved binary PSO (IBPSO), fuzzy logic (FL), artificial neural network (ANN) and more hybrid techniques [34]. Ant colony search method has been employed to find the feasible optimum solution to UCP [35-38]. Sisworahardjo and Keib [35] proposed a ACSM approach with having combination of positive feedback and distributed computation for the optimal solution of UCP prevailing the satisfaction of all the operating constraints during generating unit transition. Sharkh *et al.* [36] suggest that positive feedback and distributed computation employed ACSM in [35] for the good feasible outcome and to avoid early convergence. Unit commitment problem solved by using combination of ACSM and lamda iteration method for economic dispatch has been discussed by Sum-in and Ongsakul [37]. Flavia *et al.* [38] proposed a approach with combination of LRM and ACSM for the solution to UCP. Lagrangian relaxation method associated with discrete variables as the source of information for the ACSM for UCP. Solution to UCP has been proposed with ANN [39-40]. Sasaki *et al.* [39] discussed the ANN approach for the feasible solution to UCP and handling all the inequality constraints. Unit commitment has been improved by hour or day ahead load forecasting resulted from ANN presented by Saksornchai *et al.* [40].

A solution to UCP using modified augmented hopfield neural network by eliminating all the errors in conventional augmented hopfield network discussed by Kamh *et al.* [41]. Indhumathi *et al.* [42], Kadam *et al.* [43] and Saneifard *et al.* [44] proposed a FL approach for the feasible, reliable and optimal solution to UCP. Feasible and optimal solution to UCP is achieved by GA along with consideration of various operating constraints has been discussed by Swarup and Yamashiro [45] and Dasgupta and McGregor [46]. As the simple GA has slow convergence, so enhanced GA has been proposed to find most feasible and optimum solution to UCP provided the satisfaction of generating limitations presented by Mingyu *et al.* [47]. A price/profit solution to UCP considers the demand constraint and allocates fixed and transitional costs to the scheduled hours by GA presented by Richter and Sheble [48]. Simopoulos and Kavatza [49] discussed the SA approach to solve UCP considering ramp rate constraint and ramp rate is consider to be backward or forward

depending upon the response generated by SA. By using SA convergence rate to find the optimal solution to UCP is fast considering satisfaction of all generating limits presented by Dudek [50]. Anita and Raglend [51] proposed an approach of shuffled frog leaping algorithm (SFLA) being implemented to solve UCP and it involves local search and shuffling until a required convergence is reached. Raglend *et al.* [52] presented a profit based optimal solution to UCP by using various techniques of PSO as chaotic PSO (CPSO), new PSO (NPSO) and dispersed PSO (DPSO). Samudi *et al.* [53] proposed PSO for solving hydro thermal scheduling problem to find the global optimum solution. Zhao *et al.* [54] discussed the improved particle swarm optimization (IPSO) to find the solution to UCP. Chances for approaching the optimal solution are more in IPSO as convergence rate is very fast. Moreover this technique also employ zero one variable and penalty function to transform the linear optimization problem to non linear one considering all operating constraints.

Random search techniques individually also have limitation as slow convergence as approaching near to global optimal solutions [34]. Liu *et al.* [55] proposed a hybrid ANN and LRM approach for scheduling generating units and presumes a relationship between load demand and lagrangian multiplier used as reference for ANN. An hybrid technique employing the combination of ANN and DP to solve UCP and ANN generates a pre-schedule with respect to the load demand while DP provides a check on the stages having unnecessary running of generating units irrespective to load demand has been discussed by Ouyang and Shahidehpour [56]. Su and Hsu [57] presented a fuzzy DP (FDP) to omit the error in load forecasting to make more improved scheduling of generating units. A fuzzy logic ant colony search method has been discussed to find the global feasible solution of UCP and FL handles any uncertainty occur in the system while ACSM handles scheduling of units discussed by Sharkh *et al.* [58]. A combination of FL and stochastic SA provides the solution to UCP discussed by Saber *et al.* [59]. Optimal UC by employing hybrid ACSM and PLM includes the flexibility of priority list method is reinforced and ant system algorithm gain the benefit of using bias information for improving the performance during search process for the obtaining the optimal solution in a reasonable time presented by Chusanapiputt *et al.* [60]. Mantawy *et al.* [61] proposed a hybrid approach i.e. integrating GA, tabu search (TS) and SA for the solution of UCP and method shows that offsprings are generated by TS and SA accelerates the convergence rate of GA towards the optimality of solution to UCP. Balci and Valenzuela [62] discussed a technique with combination of PSO with LRM to find the most feasible optimal solution to UCP In proposed PSO is used to evolve lagrangian multipliers and optimization problem is solved using DP. Therefore unit commitment plays a significant

role to improve the economic structure of power industry by optimal scheduling table for the units in power plant to be online or offline in respect to the demand of electricity. So a great deal of money can be saved.

As the optimization problems grows in dimensionality leads to development of the random search techniques like EP, GA and ACSM, FL ANN, differential evolution (DE) [34]. Out of these EP has fast convergence rate to find the local and global optimal solution as it searching in respect to distance of feasible optimal solution. Three types of EP has been developed i.e. classical evolutionary programming (CEP), fast evolutionary programming (FEP) and improved fast evolutionary programming (IFEP) [63]. All the three techniques work on the basis of placement of optimum solution position in search space. For local search CEP evaluates the optimal point, global optimal solution FEP is used and depending upon the distance of global optimum point from the starting point in search area IFEP is came into picture [64]. Few research papers depicts the problems associated with power system has been solved by using EP. Feuring *et al.* [65] presented the EP being employed to fuzzy flexible program by maximizing the objective function i.e. changes into multi objective fuzzy linear programming problem. A parallel EP approach for solving optimal power flow problem and is less sensitive to the starting point in the search area and generating units cost curves discussed by Lo *et al.* [66]. Othman *et al.* [67] proposed a EP for optimization of generation capacity of unit to find out the capacity benefit margin of that particular area. Chung *et al.* [68] provides a hybridized technique comprising of DE and EP used for the reactive power flow as hybridization of two techniques overcome the drawback of differential evolution of requirement large population size to avoid premature convergence. Minimization of the distribution feeder losses has been using improved by using EP and achieved by minimizing the real power losses as well as on voltage and current constraints subjected to radial network structure has been discussed by Cheng *et al.* [69]. Lai and Ma [70] presented a EP technique for optimal power flow in power system by minimizing the real power losses as EP being coupled with active and reactive power flow. Sinha *et al.* [71] discussed the economic load dispatch (ELD) problem has been achieved using EP as to enhance speed and robustness as comparison earlier gradient search technique.

Optimal reactive power planning has been achieved by employing EP and evaluation of real and reactive power for the global optimal solution provide by Lee and Yang [72]. Ma [73] proposed a optimal technique to unified power flow on transmission network to improve voltage profile in particular area is simplified by using EP. Abido and Magid [74] discussed an optimal designing of power system stabilizer (PSS) has been achieved by searching the

optimal setting of power system stabilizer and is achieved by employing EP under different loading condition and disturbances. EP and GA techniques being employed for finding the location of best available parameter for proper load modeling. So power system dynamic load identification and stability has been achieved has been provided by Zhu *et al.* [75]. Wong and Yuryevich [76] proposed a EP technique for resolving the environmentally constrained ELD problem to improve system speed and robustness. An EP approach to present voltage stability margin enhancement using optimal reactive power support with implementation of reactive power support widens the voltage stability margin with improvement of voltage profile and less transmission losses discussed by Hassim *et al.* [77]. Dasan *et al.* [78] depicts that optimal sitting and sizing of distributed system for a mixed realistic load model results into reduction of losses by EP and moreover voltage profile being improved. An EP approach to optimal reactive power dispatch and voltage control of bus power system leads to more economical operation has been discussed by Wu and Ma [79]. Song *et al.* [80] proposed a fuzzy controlled EP for network reconfiguration for loss reduction in distribution system provides binary control parameter and speed up the optimization process.

Cebrian and Kangan [81] discussed that a reconfiguration of radial distribution system under various load conditions can be easily tackled by EP to improve the power quality. A dynamic economic dispatch problem is resolved by employing EP leads most feasible global optimal solution provided by Aziz *et al.* [82]. Jeevananthan *et al* [83] proposed a EP approach for placement of area integration pulse width modulation technique to get a required sinusoidal output providing that total area for every half pulse in each half cycles are same. Ma and Wu [84] proposed EP to identify the generator parameters based on the measurements on generator output. Tsay *et al.* [85] suggested solving ELD of cogeneration system considering steam, emission and power constraints using EP. Sood [86] proposed a solution to optimal power flow for efficient operation and planning in power system with implementation of EP. Shi and Xu [87] discussed EP provides a global optimized solution to multi-objective operation of power system considering equality and inequality constraints. Wong and Algie [88] proposed EP for optimal dispatch of heat and power for cogeneration system satisfying load demand. Maintenance scheduling problem of power generation and transmission system is achieved with incorporation of EP as suggested by Sharkh and Keib [89]. Somasundaram *et al.* [90] discussed the solution to ELD problem without considering prohibiting zones and with consideration of penalty factor achieved by employing FEP. So and Li [91] proposed that EP plays significant role in coordinating over current relay grading and capable of escaping from local minima for all power system constraints and

configurations. Therefore EP has been applicable to many problems associated with power system. Evolutionary programming has faster convergence rate to reach the global optimum point, easy to understand and implement. Its work depend upon the type of mutation implemented to reach the optimal solution as it able to find the optimal point in local as well as global search area depending upon the distance of optimum point from the searching start point the search area.

1.3 Author's Contribution

Unit commitment of thermal units has been carried out considering the combination of scheduling of generating units along with optimum dispatch of power using EP. Cost function include production cost and starting cost of generating units for generating power, which is to minimized. Three types of EP i.e. CEP, FEP and IFEP implemented for the solution of thermal unit commitment problem and finally optimal generation scheduling is obtained with optimum power. Results obtained from applied approach are compared with results obtained from various optimization problem solving techniques.

1.4 Organization of Thesis

The thesis work carried out has been categorized into six chapters. Chapter 1 covers the brief introduction, summary of work carried out by various researchers, author's contribution and outline of thesis. Chapter 2 describes the thermal unit commitment problem. Chapter 3 explains the methodology of EP and its various types i.e. CEP, FEP and IFEP. Chapter 4 covers the solution approach to thermal unit commitment problem using evolutionary programming algorithm. Chapter 5 covers results and discussion part. Finally chapter 6 explains the conclusion and scope of future work.

CHAPTER 2

THERMAL UNIT COMMITMENT

2.1 Introduction

In today's world scenario, as the demands for electricity increases and still keep on increasing, it's being difficult to make a balance between generating power and load demand. So unit commitment is a crucial step to utilize the proper commitment of all the operating units in achieving the overall goal of economic and reliable operation of the power system [92]. Therefore to "commit" a generating unit implies to turn to "turn it on" that is, to bring up to the desired speed, synchronize it and connect it to the system so that it can deliver power to that network. The problem of "commit enough units and leave them online" is one of economics [2]. So aim of economic scheduling of generators is to guarantee the optimum combination of generating units connected to a power system to supply the load demand. So unit commitment handles the unit generation schedule in a power system to meet the forecasted demand for minimizing operation cost and satisfying the operating constraints such as load demand and system reserve requirement for a specified period of time that usually varies from 24hours to a week.

Unit commitment determines the schedule of a unit that is when to start-up and shut down within a prescribe time period [93]. Constraints put limitation on the start-up and shutting down units. The total cost incurred in a thermal power plant includes total unit production cost, start-up and shutdown cost. Production cost includes cost of fuel required by a given set on line generating unit to meet the load demand of the system. Start-up and shutdown cost includes the cost incurred to bring the unit in online and offline stage as per requirement of electricity. The constraints to be satisfied during unit commitment are individual generating units, minimum up time, minimum down time, capacity limits, generation limit for the first and last hour, limited ramp rate, group constraint, power balance constraint, spinning reserve constraint, hydro constraint [94]. The high dimensionality and combinatorial nature of the unit commitment problem curtail attempts to develop any rigorous mathematical optimization method capable of solving the whole problem for any real-size system. So it's necessary to solve the unit commitment problem [1]. As the way human daily routine follow various cycles. In the same way in electric power system, total load demand also cyclic changes i.e. varies from day time to night time or from weekdays to weekends due to cyclic changes in human and industrial activities. So to commit all the generating units to serve the varying load demands is put more financial impacts. Therefore

it's necessary to decommit the generating units when they are not needed to save a great deal of money [95].

2.2 Formulation of Thermal Unit Commitment Problem

Objective function:-

To minimize the cost as under

$$F \text{ cost} = [P \text{ cost}(J, I) + S \text{ cost}(J-1, L; J, I) + F \text{ cost}(J-1, L)] \quad (2.1)$$

where

$F \text{ cost}$ = Least total cost at state (J, I) .

$F \text{ cost}(J-1, L)$ = Minimum total cost to arrive at state (J, I) .

I = No of successful combination.

J = Total No's of hours.

L = Reduced number of strategies that depends on the experimenting with a particular program. (discarding the highest cost schedules at each time interval and saving only the lowest N paths or strategies).

N = No of strategies, or paths, to save at each step = $(2^{\text{no of units}} - 1) = 2^N - 1$

$P \text{ cost}(J, I)$ = Production cost for state (J, I) .

$S \text{ cost}(J-1, L; J, I)$ = Transition cost from state $(L-1, L)$ to state $(J-1, I)$.

State (J, I) = I^{th} combination at hour J

Subjected to various constraints discussed as under.

2.3 Constraints in Unit Commitment

There are lots of constraints in UCP i.e. operating and global constraints. Operating constraints as power equality and inequality constraints, minimum up and down time constraints and also load demand and reserve requirements [9].

2.3.1 Type of Units

In thermal plant, there are generating units segregates on the basis of their operation [96]:-

- Must run units: These units include pre-schedule units which must be online, due to operating reliability and/or economics consideration.
- Must out units: Units which are on forced outages and maintenance are unavailable for the commitment and they are must out units.

- Units on fixed generation: These are units which are prescheduled and have their generation specified for certain period. A unit on fixed generation is automatically a must run unit for the designated time period.

2.3.2 Thermal Unit Constraint

Thermal power plants can be treated with two approaches as first approach is cooling. And second approach is banking or hot start up cost. So cooling rate of a unit i.e. exponential in nature [97].

Start up cost when Cooling is given as under:

$$F_c(1 - e^{-t/\alpha}) \times F + F_f \tag{2.2}$$

where

F_c = Cold Start Cost.

F = Fuel Cost.

F_f = Fixed Cost (Crew Cost, Maintenance Cost).

t = Time (h) the unit was cooled.

α = Thermal time Constant for the unit.

it may be economical to keep the unit in hot standby. The choice between shutting down and hot standby is depend on the two cost curves and length of the time a unit is to be out of service. Generally a constant fuel is required to maintain the temperature and pressure in the boiler. Thus standby cost is assumed to be linear function of shutdown time [98].

Start up cost when banking or hot start up is consider is

$$F_c(1 - e^{-t/\alpha}) \times F + F_t \tag{2.3}$$

where

F_t = Cost of maintaining a unit at operating temperature.

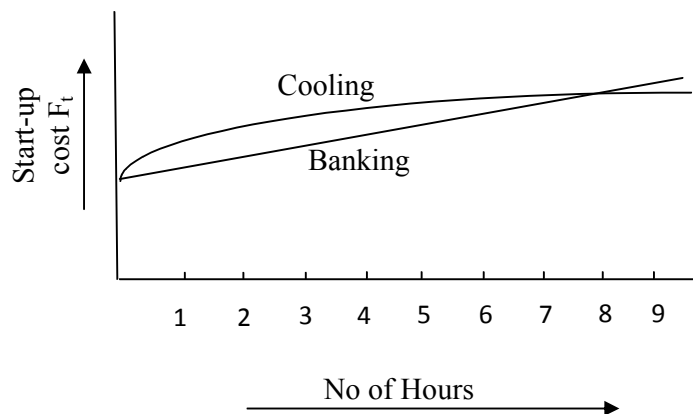


Figure 2.1 Time dependent start-up cost curve.

2.3.3 Spinning Reserve

Spinning reserve describes the total amount of generation available from all units synchronized (i.e. spinning) on a power system, subtracting the present load supplied and losses being incurred during that period. Spinning reserve must be carried out in such a way that the loss of one or more units does not cause too far drop in system frequency. Spinning reserve must obey certain rules which will specify that reserve must be capable of making up the loss of most heavily loaded unit in a given period of time [16].

$$\sum_{i=1}^{NG} U_{ij} P_i^{\max} \geq PD_j + P_j^r \quad (2.4)$$

where

NG = Total number of generating units.

P_i^{\max} = Maximum power generated by i^{th} unit.

P_j^r = Spinning reserve requirement at j^{th} hour.

PD_j = Total power demand at j^{th} hour.

U_{ij} = Commitment by i^{th} unit at j^{th} hour.

2.4 Other constraints

Constraints pertaining to operation of a generating station are termed as constraints that are required for optimal operation of generating units.

2.4.1 Fuel Constraint

A system in which some units have limited fuel, or else have constraints that require them to burn a specified amount of fuel in a given time, presents a most challenging unit commitment problem. In case of unit commitment fuel cost is subdivide into two categories as production cost or generation cost for power generation and transitional cost. The transitional cost is generally associated with starting and shutdown of a generating unit. Production cost is the cost incurred for the generation of power depends upon the load demand [90].

2.4.1(a) Transitional Cost

Transitional cost is the cost associated with shutdown and starting of a particular generating unit. Normally shutdown cost is considered as fixed cost which is independent of length of time for which the unit is running before shutdown. So ultimately transitional cost is considered as time dependent cost i.e. minimum down time and cold start-up time. It depends

upon two cost curves i.e. hot startup cost and cold startup cost ($S \cos t_{ij}^k$) and length of time a unit is out of service. So it is preferable to unit on hot standby instead of shutdown as cost curve for hot standby is linear function of shutdown time [54, 88].

$$H_i^{off} = MDT_i + T_i^{cold} \quad (2.5)$$

where

T_i^{cold} = Cold start-up time for unit i .

MDT_i = Minimum down time for unit i .

Then a start up cost can be hot start-up cost or cold start-up as under.

if

$$\{MDT_i \leq T_{ij}^{off} \leq H_i^{off}\} \text{ then } S \cos t_{ij}^k = S_{hi} \quad (2.6)$$

$$\{T_{ij}^{off} > H_i^{off}\} \text{ then } S \cos t_{ij}^k = S_{ci} \quad (2.7)$$

where

Start-up or transitional cost for unit

S_{hi} = Hot start-up cost for unit i .

S_{ci} = Cold start-up cost for unit i .

T_{ij}^{off} = Unit i off time during an j^{th} hour.

2.4.1(b) Production Cost

Production cost is the cost incurred on fuel for the generation of power by the generating cost to meet the load demand. So main overall objective of unit commitment is to minimize the production cost. Numerous methods of economic dispatch are there to minimize production cost. Units are assumed to have linear piece wise linear generation cost curves and loading is being carried with unit having lowest incremental cost and dispatch continues until demand fulfill. Dispatching of power is carried out within the limit of generation limits and satisfied all the operating constraints and also power reserve constraint [12, 99].

$$F_i(P_{ij}) = a_i + b_i P_{ij} + c_i P_{ij}^2 \quad (2.8)$$

where

a_i, b_i and c_i = Cost coefficients.

$F_i(P_{ij})$ = Total fuel cost incurred for generating the power by i^{th} unit in j^{th} hour.

P_{ij} = Power generated by i^{th} unit in j^{th} hour.

2.4.2 Power Equality Constraint

The total generated power at each hour should be equal to the load of the corresponding hour.

$$\sum_{i=1}^{NG} P_{ij} U_{ij} = PD_j \quad (2.9)$$

where

P_{ij} = Real power generation by i^{th} unit at j^{th} hour.

PD_j = Total power demand at j^{th} hour.

P_L = Transmission losses at j^{th} hour.

U_{ij} = Commitment by i^{th} unit at j^{th} hour.

2.4.3 Power Inequality Constraint

The Generator of the unit is under its minimum and maximum limit.

$$P_i^{\min} \leq P_{ij} U_{ij} \leq P_i^{\max} \quad (2.10)$$

where

P_i^{\max} = Maximum real power generation limit of i^{th} unit.

P_i^{\min} = Minimum real power generation limit of i^{th} unit.

2.4.4 Minimum up/down time constraint

The minimum up/down time constraints indicate that a unit must be on/off for a certain number of hours before it can be shut off or brought online, respectively. It means a unit cannot be shut or start immediately as it required some minimum period of time to shutdown from commit state or to start from decommit state.

$$T_{ij}^{on} \geq MUT_i \quad (2.11)$$

$$T_{ij}^{off} \geq MDT_i \quad (2.12)$$

where

MUT_i = Minimum up time.

MDT_i = Minimum down-time.

T_{ij}^{on} = Time duration during which the i^{th} unit is continuously on in j^{th} hour.

T_{ij}^{off} = Time duration during which the i^{th} unit is continuously off in j^{th} hour.

2.4.5 Crew Constraint

If a plant consists of two or more units, it's not possible to make all the units on at the same time as there are not enough crew members to attend both units at the starting up of units. So it also puts limitation on unit commitment to some extent [1].

CHAPTER 3

EVOLUTIONARY PROGRAMMING

3.1 Introduction

A global search technique for searching a feasible optimal solution based on finite state machine model in early stages i.e. evolutionary programming (EP) suggested by L. J. Fogel and it follows the darwin's theory of survival of fittest [100]. Evolutionary programming depicts a relationship between parents and child (offspring). Many optimization problems in real space are solved using EP. Evolutionary programming is an artificial intelligence method in which optimization algorithm is the main engine for the process of three steps as natural selection, mutation and finally competition. According to the problem the basic strategy employs the selection of best fittest offspring to be parents for next offspring and leads to optimal solution of problem. It can be implemented to real life problems or practical problems [101].

3.2 EP as Probabilistic Optimization Technique

Various optimization techniques like classical technique i.e branch and bound method (BABM), priority list method (PLM), dynamic programming (DP), lagrangian relaxation method (LRM) [3]. Classical techniques although are reliable and fast in solving the various optimization problems, but these are having some limitations of becoming slow and more complex as the problem increases dimensionally [32]. With the advancement in the field of optimization problem solution strategies, random search techniques are come forward to solve optimization problems i.e. ant colony search method (ACSM), fuzzy logic (FL), genetic algorithm (GA) artificial neural network (ANN), particle swarm optimization (PSO) and EP etc provides random search for the optimal solution to various optimization problems [34]. Out of above mentioned random search techniques EP is good convergence to global optimal solution to optimization problems. Evolutionary programming is a stochastic optimization strategy, which places emphasis on the behavioral linkage between parents and their offsprings. It is powerful optimization technique which does not first and second derivatives of objective function [63]. Based on probabilistic search scheme, EP generates the parent vectors distribute uniformly in the intervals within the limits and leads to global optimum solution over a number of attempts or iterations.

The main stages of EP are initialization, creation of offspring vectors by mutation and finally competition and selection to evaluate the optimal solution, so common underlying

idea that come out is given a population of individuals or parents, environmental pressure causes the natural selection based on survival of fittest and finally reach the global optimum point [64]. In EP recombination or mutation is applied to each candidate or parent resulted into one or more new candidates (offspring) which competes with main parents on the basis of their fitness values and selected to undergo mutation for the next generation. This process repeats until search reaches the global optimal point. To reach the global optimum point in EP two fundamental forces are take into account i.e. variation operator that creates the necessary diversity and facilitates novelty and quality selection pushing force [102]. The combined action of variation and selection force leads to improve the fitness value in consecutive populations. Evolutionary programming is adaptive in nature as due to the environmental requirements optimize the objective function and makes the population adapt to the environment better and better. Therefore we can say that evolutionary searching process for optimal solution is stochastic. In selection process individuals having good fitness value have more chances of selection as compared to less fit individual, but even a weak or less fit individuals have chances of being survive. Similarly mutation process generates new individuals randomly [103]. Therefore optimization using EP can be summarized in two major steps [102]:

- Mutate the solution in main parents or population.
- Select the next generation from the mutated and current solution through competition criteria.

3.3 Types of Evolutionary Programming Techniques

Depending upon type of mutation process evolutionary programming techniques categorized into three categories [90, 64]:-

- Classical Evolutionary programming (CEP).
- Fast Evolutionary Programming (FEP).
- Improved Fast Evolutionary Programming (IFEP).

All types of EP are describes in detail as under.

3.3.1 Classical Evolutionary programming

Classical evolutionary programming technique employing Gaussian mutation operator with mean as zero and standard deviation is one. CEP with self adaptive mutation performs much better than CEP without self adaptive mutation. In CEP for generation of offspring gaussain or normalized random variables are undertaken. For local optimal solution CEP performs better as it takes mall steps to find the global optimum solution if it lies within local

neighborhood region. Due to its limitation of searching global solution in local neighborhood region, it has slow convergence rate to the optimal solution if it lies far from local search area. It can also be implemented into some unimodal functions and multimodal functions with some local minima as it provide fine tuning to find the global optimum solution [102]. Equation for the criterion of offspring using CEP is mentioned under.

$$P_{ij}^{k+M} = P_{ij}^k + Sd_{ij}^k (Nor()) \quad (k = 1, 2, 3 \dots M) \quad (3.1)$$

where

$Nor()$ = Normalized random number.

P_{ij}^k = Main parents or individuals for k^{th} individual.

Sd_{ij}^k = Standard deviation for k^{th} individual.

P_{ij}^{k+M} = Offspring generated from k^{th} individual

M = Total number of main population or parents.

3.3.2 Fast Evolutionary programming

Evolutionary programming technique using Cauchy mutation operator for the mutation or generation of offspring is termed as FEP. Fast evolutionary programming performs more efficiently and relative have more strength to find the optimal solution. As the step size of FEP is larger, simple and straightforward to find global optimal solution. So it performs more efficiently and fast to find global optimal solution to multimodal optimization problems. Since its step size is large to find the global optimal solution, but it is only effective at the starting of evolution to find solution as the global optimal solution lies far away from starting search point. As the evolution proceeds for the solution it becomes slow or there may also be chance to selecting less optimal solution as the global solution lies very near in the searching area. Figure 3 depicts that Cauchy mutation operator generate offspring further away from main population or parents as compared to Gaussian mutation operator due to its long flat tails. So Cauchy mutation has more probability of escaping from local optimum and moreover a smaller hill around the center indicates that Cauchy mutation spends less time in exploiting the local neighborhood and thus has weaker fine tuning ability as compared to Gaussian mutation operator in small to mid range regions. So for local optimum solution Cauchy mutation as having slow convergence rate [64].

$$P_{ij}^{k+M} = P_{ij}^k + Sd_{ij}^k (C()) \quad (3.2)$$

where

$C()$ = Cauchy Random number.

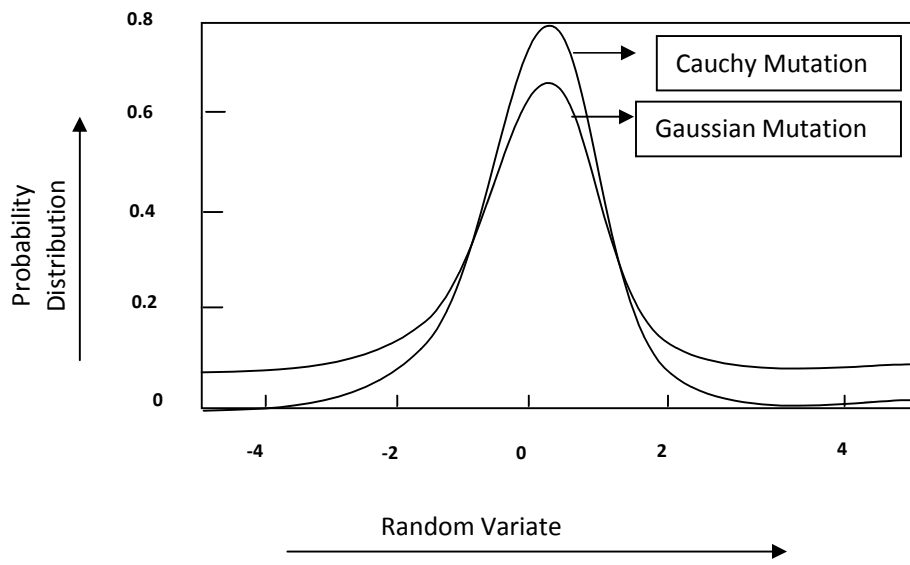


Figure 3.1 Cauchy and Gaussian Probability Distribution

3.3.3 Improved Fast Evolutionary programming

As position of global optimum solution is unknown so making choice between selection of Cauchy and Gaussian mutation operator. So instead of switching from Gaussian to Cauchy mutation operator, idea is to mix different search basis Cauchy and Gaussian mutations. In IFEP generate two offspring one from Gaussian mutation operator and one from Cauchy mutation operator. Therefore population size of IFEP is half than that required in CEP and FEP. Moreover IFEP is robust and does not require no prior knowledge of the problem to be solved [64].

$$P_{ij}^{k+M} = P_{ij}^k + Sd_{ij}^k (Nor() + C()) \quad (3.3)$$

3.4 Main parts of Evolutionary Programming

The main stages of this technique [102-103] are mentioned below:-

- Representation
- Fitness function
- Population
- Parent selection methodology
- Mutation
- Survivor Selection Mechanism
- Termination

1. **Representation:** - It is the first step mapping of real world problem into

evolutionary algorithm world that is to set up a bridge between original problem and problem solving space where evolution takes place.

2. **Fitness function:** - Evaluation function represents the task to solve in evolutionary context. It is the function or procedure that assigns a quality to evaluation. More accurately it defines what improvement means. It forms the basis for the selection thereby facilitates improvement.

3. **Population:** - Population means how many individuals have in it i.e. setting the population size. Almost in all the various applications of EPs, population size remains constant during evolutionary search. Populations form a unit of evolution and individuals are static objects not changing or adapting.

4. **Parent selection methodology:** - According to the Darwin's evolution theory the best ones survive and create new offspring. So chromosomes are selected from the population to be parents. The objective of parent selection or mating is to compare on the basis of quality and allow better individuals for the generation of offspring for the next generation. High quality individuals have more chance to be selected than those of low quality individuals. However low quality individuals are often given a small, but positive chance for selection otherwise whole search process becomes greedy and stuck to local optimum. Chromosomes can be selected from lot of ways as steady state selection, roulette wheel selection, rank selection and elitism. So therefore high quality individuals are selected for the generation of child for next generation.

5. **Mutation:-** It is also known as background operator. It delivers a modified mutant, the child or offspring of it. A mutation operator is always stochastic: its output- the child- depends on the outcome of a series of random choices. Lot of mutation operators used for generation of offspring i.e. Gaussian mutation operators, Cauchy mutation operators and mean of both Gaussian and Cauchy mutation operators as per the eq. (3.1) to (3.3).

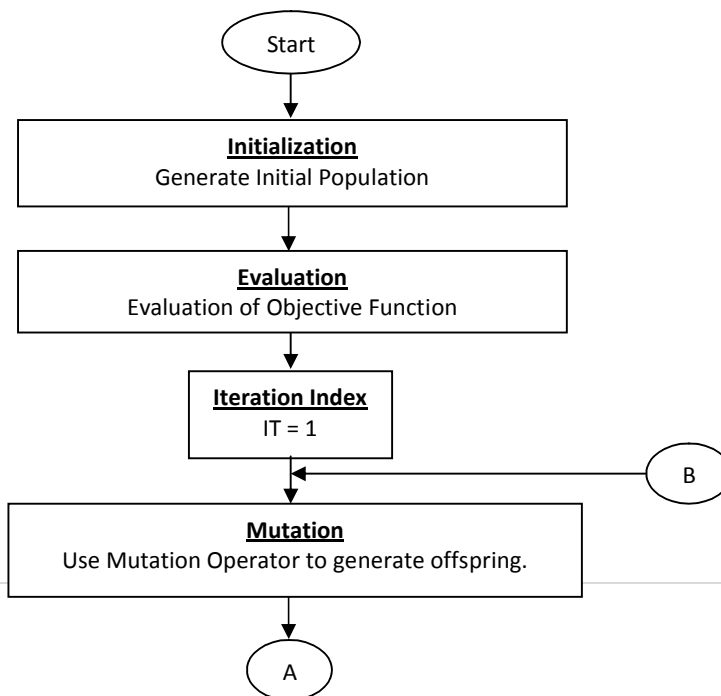
6. **Survivor Selection Mechanism:** - The role of this is similar to parent selection, but it is used in different stage of evolutionary cycle. The survival selection mechanism is called after having created the offspring of the selected parents. Selected offspring have high fitness value and higher quality. It is often called as replacement selection or replacement strategy. The preference for using replacement can be motivated by the skewed proportion of the number of individuals in the population and new created children. It means that if the no of children are two less in comparison to the size of population e.g. if the no of children are 2 and population size is 100 then two old individuals are deleted to make place of new ones. If no of children are

500 and population size is 100 i.e. proportion is not skewed then term survivor selection is appropriate.

7. **Termination:** - Termination means that end of the technique or method which are using for the solving the optimization problem to find the global optimum solution in the system. If the problem has reaches the desired fitness level coming out from searching in search area then stopping condition employed.

So EP as probabilistic optimization technique can be easily implemented to real and practical problems. Evolutionary programming is a stochastic optimization strategy shows a strong bond of main parents or individuals with their offspring as it employs a recombination or mutation operator to generate the new individuals i.e. offspring. A new generated individual undergoes a competition with main parents basis of their fitness values and step forward towards the feasible global optimum point [63]. Due to its adaptive nature, it optimizes the objective function as per the requirements and provides new population which more better adaptive to the environment. Evolutionary programming has lots of advantages as more capability of converging to global optimal solution, EP uses a population of points instead of single point, constraints pertains to optimization can be easily handled using EP, moreover EP uses only objective function information so independent of nature of search space such as smoothness, convexity or uni-modality [64,100-102]. Evolutionary programming also having some limitation as slow convergence in case of multimodal optimization problems to good near optimal solution [104].

Figure 3.2 shows the methodology of evolutionary programming technique. It includes an overview of the process strategy in evolutionary programming like initialization, fitness evaluation, mutation, elite strategy and finally the optimal solution.



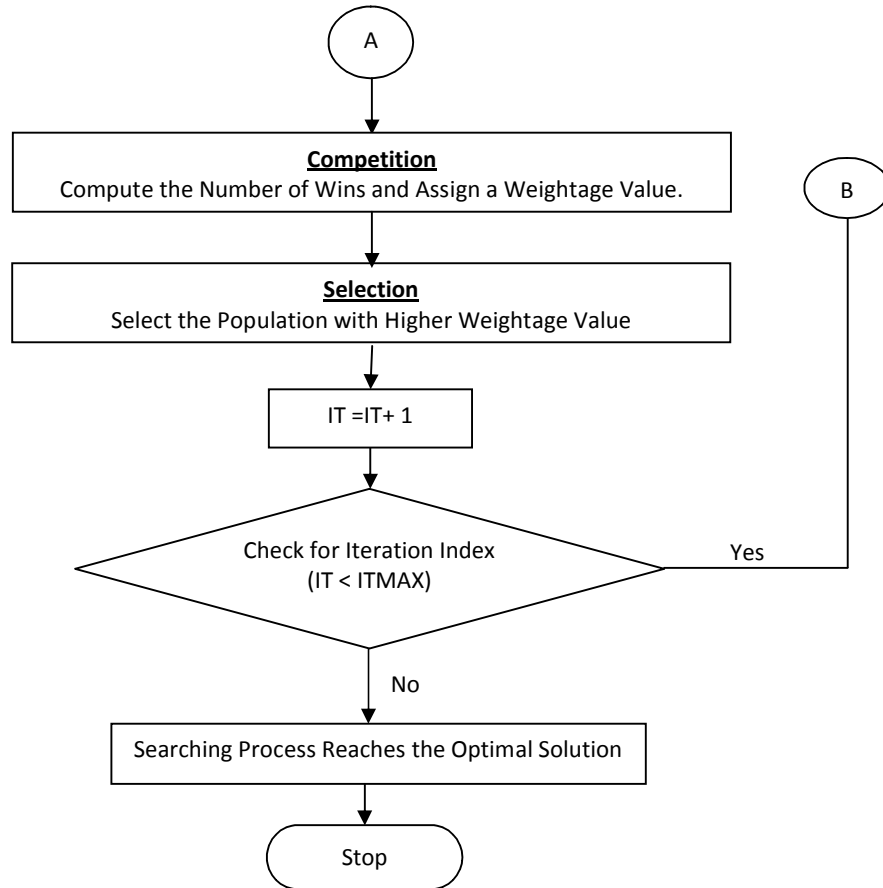


Figure 3.2 Flow Chart for Methodology of Evolutionary Programming

CHAPTER 4

THERMAL UNIT COMMITMENT USING EVOLUTIONARY PROGRAMMING

4.1 Introduction

The main purpose of thermal unit commitment problem (TUCP) is optimum scheduling of the generating units and to minimize the operating cost that include the production cost for the generation of power and start up cost for generating unit to turn on during particular hour to meet the load demand for the same hour. Thermal unit commitment deals with various operating constraints as generating limit constraints, power reserve constraint [96]. Evolutionary programming technique can be implemented by searching of state variable as generation of power of thermal plant P_i within the generating limits so that the total operating cost becomes minimum. Cost functions is defined as

Cost function is defined as under:

$$Fcost = [Pcost(J,I) + Scost(J-1,L;J,I) + Fcost(J-1,L)] \quad (4.1)$$

Subjected to

Constraints.

- **Power balance constraint**

The total generated power at each hour should be equal to the load and transmission losses of the corresponding hour.

$$\sum_{i=1}^{NG} P_{ij} U_{ij} = PD_j \quad (4.2)$$

- **Spinning Reserve Constraint**

Enough amount of power is generated to meet the load demand for any hour in case any sudden tripping/maintenance of committed unit for that particular hour

$$\sum_{i=1}^{NG} U_{ij} P_i^{\max} \geq PD_j + P_j^r \quad (4.3)$$

- **Power Inequality Constraint**

The generating units should generate the power within the generator minimum and maximum power generation limit.

$$P_{ij}^{\min} \leq P_{ij} U_{ij} \leq P_{ij}^{\max} \quad (4.4)$$

- **Minimum-up Time Constraint**

The minimum up constraints indicate that a unit must be on for a certain number of hours before it can be shutdown.

$$T_{ij}^{on} \geq MUT_i \quad (4.5)$$

- **Minimum-down Time Constraint**

The minimum down time constraints means that a unit must be in off state for a certain number of hours before it can be brought online

$$T_{ij}^{off} \geq MDT_i \quad (4.6)$$

4.2 Solution Approach to TUCP.

A non linear TUCP follows the step wise approach to reach the global optimal solution. Step wise approach is discussed in categorized into two parts as first part deals with the random generation schedule of the generating units of thermal power plant and finally the handling of constraints with exterior penalty factors along with their repairing and optimal dispatch of power with the implementation of evolutionary programming (EP) discussed as under.

4.2.1 Initialization of Population

This is first forward step for solution to TUCP. It deals with random initialization of generating schedule and power for all the generating units in thermal power plant discuss in detail as under.

4.2.1.1 Random Initialization of Generating Units

In initialization of the individuals, random generation of the generating units is carried out. Each unit status as on or off i.e. 1 or 0 as a gene by generating uniform random number and all unit status for each hour considered as sub-chromosomes. So ultimately T sub-chromosomes over a time horizon. Therefore individuals represent the unit status for a particular time period and can be obtained by comprising that if the value of uniform random number is greater than 0.5 then unit consider in on state (1) otherwise unit is in off state (0) can be represented as under.

$$U_{ij}^k = rand(), \text{ If } U_{ij}^k > 0.5 \text{ then } U_{ij}^k = 1 \text{ otherwise } U_{ij}^k = 0 \quad (4.7)$$

Final generated schedule of generating units is represented as per eq. (4.8)

$$U = \begin{bmatrix} u_{1\ 1}^1 & u_{1\ 2}^2 & \cdots & u_{1\ j}^k \\ u_{2\ 1}^1 & u_{2\ 2}^2 & \cdots & u_{2\ j}^k \\ \vdots & \vdots & \vdots & \vdots \\ u_{N\ GJ}^1 & u_{N\ GJ}^2 & \cdots & u_{N\ GJ}^L \end{bmatrix} \begin{pmatrix} i = 1, 2, 3 \dots NG \\ j = 1, 2, 3 \dots J \\ k = 1, 2, 3 \dots M \end{pmatrix} \quad (4.8)$$

where

U_{ij}^k = On or off (1 or 0) status for unit i at time j for k^{th} individual

M = Total number of individuals or population

4.2.1.2 Random Power Initialization of Individuals

On random initialization of generating unit for each individual, power is generated randomly by each unit for each individual and represents as per below mentioned equation.

$$P_{ij}^k = U_{ij}^k \left(P_i^{\min} + rand() \times (P_i^{\max} - P_i^{\min}) \right) \quad (4.9)$$

where

P_{ij}^k = Power generated by unit i^{th} in j^{th} hour for k^{th} individual

P_i^{\min} = Minimum power generated by i^{th} unit.

$rand()$ = Uniform random number ranging between 0 to 1.

4.2.2 Unit Scheduling based on Priority Listing

Before priority list scheduling of unit, there must be knowledge of fuel cost for generation of power described as under.

Cost function

$$F_i(P_{ij}) = a_i + b_i P_{ij} + c_i P_{ij}^2 \quad (4.10)$$

where

a_i, b_i and c_i = Cost coefficients.

$F_i(P_{ij})$ = Total fuel cost incurred for generating the power by i^{th} unit in j^{th} hour.

P_{ij} = Power generated by i^{th} unit in j^{th} hour.

Unit scheduling of plant based on priority list of generating unit parameters is achieved on the basis of average fuel cost of each unit operating at its maximum power output. Average full load cost is defines as under.

$$\alpha_i = \frac{F_i(P_i^{\max})}{P_i^{\max}} = \frac{a_i}{P_i^{\max}} + b_i + c_i \times P_i^{\max} \quad (4.11)$$

where

α_i = Average fuel cost of i^{th} unit

Generating units are categorized in ascending order with respect to the average fuel cost α_i .

Unit having lowest value of α_i is having the highest priority for the dispatching the power.

So finally a schedule of generating units is generated but without making a check on the satisfaction of all the operating constraints. So next section deals with the same.

4.3 Handling of Constraints

This section deals with handling of constraints for optimal scheduling of generating units and optimal dispatch of power with the implementation of EP. During the up-gradation process if the decision variable i.e. thermal power (P_{ij}) violate its limit then it is set to corresponding limit.

4.3.1 Power Reserve Constraint

During the commitment of generating units maximum power of units must be equal to or greater than the load demand and spinning reserve for the particular period of time period.

$$\sum_{i=1}^{NG} U_{ij} P_i^{\max} \geq PD_j + P_j^r \quad (4.12)$$

If the maximum power of committed unit does not meet both the load demand and spinning reserve (SR) requirement then generating unit is penalized by exterior penalty factor (E_1).

$$err = \left(\sum_{i=1}^{NG} U_{ij} P_i^{\max} - PD_j - P_j^r \right) \quad (4.13)$$

$$E1 = (err)^2 \times \text{large positive number} \quad (4.14)$$

4.3.2 Minimum-up and Down Time Constraint

Minimum-up and down time means that generating unit once commit/decommit cannot be turned off/on immediately. Minimum-up and down time can be computed and evaluated as under.

$$T_{ij}^{on} = \begin{cases} T_{ij-1}^{on} + 1 & \text{if } U_{ij} = 1 \\ 0 & \text{if } U_{ij} = 0 \end{cases} \quad \begin{matrix} (i = 1, 2, 3 \dots NG) \\ (j = 1, 2, 3 \dots J) \end{matrix} \quad (4.15)$$

$$\text{if } U_{ij} = 0 \ \& \ U_{ij-1} = 1 \ \text{then} \quad (4.16)$$

$$\begin{cases} T_{ij}^{on} \geq MUT_i & E_2 = 0 \\ \text{otherwise } E_2 = & \text{large positive value} \end{cases} \quad (4.17)$$

$$T_{ij}^{off} = \begin{cases} T_{ij-1}^{off} + 1 & \text{if } U_{ij} = 0 \\ 0 & \text{if } U_{ij} = 1 \end{cases} \quad (4.18)$$

$$\text{if } U_{ij} = 1 \ \& \ U_{ij-1} = 0 \ \text{then} \quad (4.19)$$

$$\begin{cases} T_{ij}^{off} \geq MDT_i & E_3 = 0 \\ \text{otherwise } E_3 = & \text{large positive value} \end{cases} \quad (4.20)$$

where

E_2 & E_3 = Exterior penalty factors for violation of constraint.

4.3.3 Decommittment of Excess Units

As due to the repairing of minimum-up time and down time constraint, some generating units lead to excessive spinning reserve. So unnecessary committed units must be decommitted to minimize the operating cost or production. Decommit the generating units starting from the unit having high value of average full load cost and then proceed toward the unit having lowest value of average full load cost providing no violation of SRC and minimum-up and down time constraint. So finally an optimal generation scheduling is obtained and dispatch of power for the same.

4.3.4 Power Equality Constraint

Power generates by generator must be equal to meet the load demand PD_j for a particular interval of time. If the power generated by the unit does not meets the load demand then the generating unit is penalized.

$$\begin{cases} \sum_{i=1}^{NG} P_{ij} U_{ij} = PD_j & E_4 = 0 \\ \text{otherwise } E_4 = & (\text{err})^2 * \text{large positive value} \end{cases} \quad (4.21)$$

where

$$\text{err} = \left(\sum_{i=1}^{NG} P_{ij} U_{ij} - PD_j \right)$$

E_4 = Exterior penalty factor for violation of equality constraint.

4.4 Objective function

Objective function includes the operating cost and penalty for violation of constraints is as under.

Minimize

$$F \text{ cost} = \left[P \text{ cost}(J, I) + S \text{ cost}(J-1, L; J, I) + F \text{ cost}(J-1, L) + E_1 + E_2 + E_3 + E_4 \right] \quad (4.22)$$

Subjected to constraints with respect eq. (4.2) to (4.6).

The elaborated steps are given in algorithm-I.

Algorithm-I

1. Compute the starting cost as per eq. (2.5) to (2.7).
2. Randomly generation of power for each generating unit as per eq. (4.9).
3. Objective function is computed for each parent as per eq. (4.21).
4. Compute the minimum value $(F \text{ cost})^{\min}$ of operating cost for all the parents.
5. Standard deviation is obtained as under.

$$Sd_{ij}^k = \beta \times \frac{(F \text{ cost})_{ij}^k}{(F \text{ cost})^{\min}} (P_i^{\max} - P_i^{\min}) \begin{matrix} (i = 1, 2, 3 \dots NG) \\ (j = 1, 2, 3 \dots J) \\ (k = 1, 2, 3 \dots M) \end{matrix} \quad (4.23)$$

where

$(F \text{ cost})^k$ = Operating cost all the parents.

β = Scaling factor.

6. For each parent population i.e. (P_{ij}^k, Sd_{ij}^k) , offspring P_{ij}^{k+M} are created with either of three evolutionary programming techniques as under.

6.1 Classical evolutionary programming (CEP)

In CEP Gaussian or normalized mutation operator is employed for the generation of offspring represented as under.

$$P_{ij}^{k+M} = P_{ij}^k + Sd_{ij}^k (Nor()) \quad (4.24)$$

6.2 Fast evolutionary programming (FEP)

Evolutionary programming technique using Cauchy mutation operator for the mutation or generation of offspring is termed as FEP.

$$P_{ij}^{k+M} = P_{ij}^k + Sd_{ij}^k (C()) \quad (4.25)$$

6.3 Improved fast evolutionary programming (IFEP)

Improved fast evolutionary programming technique employs both the Gaussian and Cauchy mutation operator and represented as under.

$$P_{ij}^{k+M} = P_{ij}^k + Sd_{ij}^k (Nor() + C()) \quad (4.26)$$

7. Make a check for offspring generation to be lie within the generating limits in respect to the eq. (4.2) to (4.6).
8. Objective function is evaluated for each offspring also as per eq. (4.21).

- 9 New standard deviation $Sd_{ij}^{k'}$ is evaluated from the standard deviation Sd_{ij}^k calculated in step 4 and factor τ and τ' as under [64].

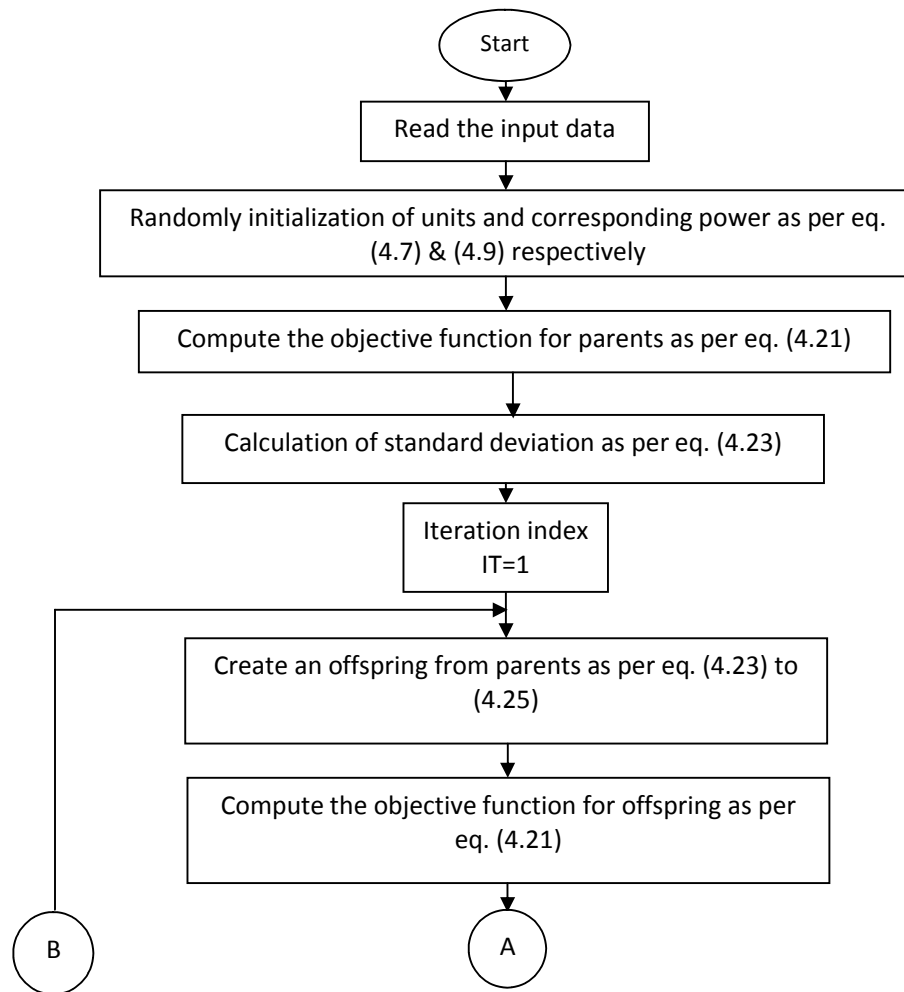
$$Sd_{ij}^{k+M} = Sd_{ij}^k \times \exp(\tau' \times Nor() + \tau \times C()) \quad (4.27)$$

where

$$\tau = (\sqrt{2\sqrt{NG}})^{-1} \quad (4.28)$$

$$\tau' = (\sqrt{2 \times NG})^{-1} \quad (4.29)$$

- 10 Conduct a competition between the parents (P_{ij}^k, Sd_{ij}^k) and offsprings $(P_{ij}^{k+M}, Sd_{ij}^{k+M})$ on the basis of their objective function and assigned some weightage value or wins.
- 11 Population having highest number of wins or having higher weightage value are selected as parents (P_{ij}^k, Sd_{ij}^k) for the generation of offsprings $(P_{ij}^{k+M}, Sd_{ij}^{k+M})$ for the next iteration.
- 12 Repeat the above steps step 5 to 11 to obtain a optimal solution.



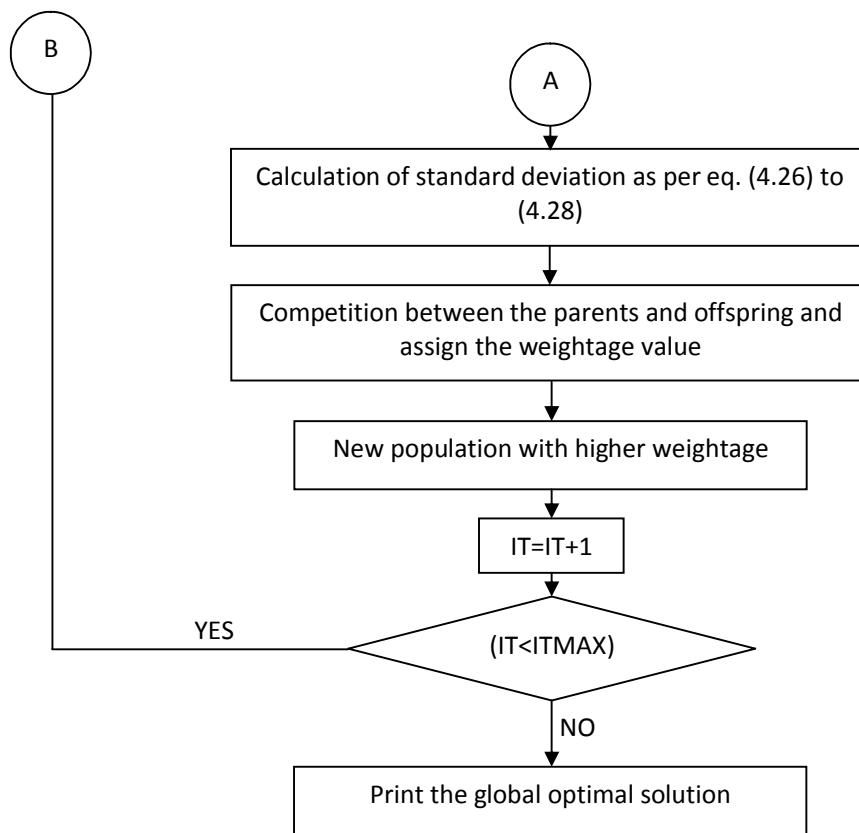


Figure 4.1 Flow Chart for Unit Commitment using Evolutionary Programming

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Test Problem

In the thesis work, three types evolutionary programming approaches i.e. classical evolutionary programming (CEP), fast evolutionary programming (FEP) and improved fast evolutionary programming (IFEP) are applied for the solution of thermal unit commitment problem (TUCP) along with the minimization of objective function. Evolutionary programming is tested on two test problems comprising of 4 generating units and 10 generating units as given in appendix –I.

5.2 Results and Comparison

5.2.1 Test Case-1

Three types of EP are applied for solution to TUCP for 4 generating units and results are compared with dynamic programming (DP) as shown in table 5.1.

Table 5.1- Operating cost for the three types of EP and DP for 4 generating units.

S. No.	Optimization Techniques Applied	Operating Cost for 4 Generating Units (\$)	CPU time taken for execution (Seconds)
1	CEP	76039.45	43.53
2	FEP	76250.85	38.26
3	IFEP	76153.86	39.45
4	DP	73439*	-----

As depicted from the table the operating cost obtained for the 4 generating units using FEP takes less CPU time in comparison to CEP and IFEP. Though CEP takes more time to find the optimal solution but operating cost achieved using CEP is less in comparison to FEP and IFEP. So therefore CEP is employed for the scheduling and dispatch of power for the 4 unit

commitment problem. Moreover as shown in table operating cost using DP is less in comparison to all EP approaches but it violates the minimum-up and down time constraint.*

Table 5.2- Schedule for the 4 generating units to serve the load for 8-hours using CEP.

Hour	Load (MW)	Unit number			
		P_1 MW	P_2 MW	P_3 MW	P_4 MW
1	450	228.202	221.784	0	0
2	530	289.536	183.769	56.680	0
3	600	300.000	174.319	74.360	51.315
4	540	271.870	199.360	68.762	0
5	400	205.643	134.838	59.506	0
6	280	112.953	167.037	0	0
7	290	180.896	109.100	0	0
8	500	300.000	119.989	80.000	0

5.2.2 Test Case-2

Solution to TUCP for 10 generating units thermal power plant is also carried out using three types of EP and results are compared with each other as shown in table 5.3.

Table 5.3- Operating cost for the three types of EP for 10 generating units.

S. No.	Optimization Techniques Applied	Operating Cost for 10 Generating Units(\$)	CPU time taken for execution (Seconds)
1	CEP	580544.40	73.47
2	FEP	597276.10	68.34
3	IFEP	585474.55	69.54

As depicted from the table the operating cost achieved for the 10 generating units using FEP takes less CPU time in comparison to CEP and IFEP similarly as in case of 4 generating units. Classical evolutionary programming takes more time to find the optimal solution and

moreover operating cost achieved using CEP is less in comparison to FEP and IFEP. Therefore CEP is employed for the scheduling and dispatch of power for the 10 unit commitment problem.

Table 5.4- Schedule for the 10 generating units to serve the load for 24-hours using CEP.

Hour	Load (MW)	Unit number									
		P_1 MW	P_2 MW	P_3 MW	P_4 MW	P_5 MW	P_6 MW	P_7 MW	P_8 MW	P_9 MW	P_{10} MW
1	700	326.001	374.009	0	0	0	0	0	0	0	0
2	750	416.119	333.879	0	0	0	0	0	0	0	0
3	850	455	308.005	0	87.001	0	0	0	0	0	0
4	950	403.293	361.629	73.061	112.017	0	0	0	0	0	0
5	1000	408.732	409.588	60.548	121.130	0	0	0	0	0	0
6	1100	349.294	404.007	110.542	111.313	124.843	0	0	0	0	0
7	1150	425.251	404.436	101.002	82.706	136.604	0	0	0	0	0
8	1200	396.127	455	130	100.503	118.370	0	0	0	0	0
9	1300	338.467	455	127.00	116.093	141.325	53.904	68.207	0	0	0
10	1400	414.898	455	113.832	105.629	162	77.006	61.632	10	0	0
11	1450	455	385.617	130	113.828	153.990	80	69.649	35.973	25.941	0
12	1500	448.244	445.068	94.392	56.697	125.598	80	85	55	55	55
13	1400	455	443.149	104.153	115.3575	143.711	68.616	60.011	10	0	
14	1300	365.865	398.649	130	130	142.567	71.982	60.936	0	0	0
15	1200	375.339	455	130	100.202	139.460	0	0	0	0	0
16	1050	351.531	331.487	93.012	130	143.971	0	0	0	0	0
17	1000	279.790	396.857	99.691	115.607	108.055	0	0	0	0	0
18	1100	327.702	443.922	105.718	90.656	131.999	0	0	0	0	0
19	1200	404.418	423.292	119.299	130	122.991	0	0	0	0	0
20	1400	378.499	455	109.397	110.294	141.825	77.339	85	42.6430	0	0
21	1300	308.640	455	114.282	113.370	162	69.233	77.474	0	0	0
22	1100	362.696	455	0	0	142.867	67.752	71.683	0	0	0
23	900	347.922	396.009	0	0	156.069	0	0	0	0	0
24	800	434.430	365.570	0	0	0	0	0	0	0	0

Results achieved for 4 and 10 generating units unit commitment problem using CEP is found better in comparison to IFEP, FEP and DP.

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion

Solution to thermal unit commitment problem (TUCP) is carried out using three types of evolutionary programming (EP) techniques i.e. classical evolutionary programming, fast evolutionary programming and improved fast evolutionary programming and tested for solving four and ten generating units. Results obtained from the applied approach are comparable in comparison to the result obtained by dynamic programming.

6.2 Scope for Future Work

Scope of work after incorporating EP for solving TUCP is summarized as:

- The applied approach can be tested for large number of generating unit system.
- Evolutionary programming can also be implemented for hydro-thermal unit commitment problem.
- Evolutionary programming can be hybridized with other random search optimization techniques (particle swarm optimization (PSO), differential evolution (DE), hybrid PSO) for the solution TUCP.

APPENDIX

APPENDIX-I

Input data for 4 generating unit and 10 generating units along with load demand for the respective case in mentioned below [105].

1. Input data for 4- generating units.

Data Description	Unit 1	Unit 2	Unit 3	Unit 4
P_i^{\max} (MW)	300	250	80	60
P_i^{\min} (MW)	75	60	25	20
a_i (\$/h)	684.74	585.62	213.00	252.00
b_i (\$/MW h)	16.83	16.95	20.74	23.60
c_i (\$/MW ² h)	0.0021	0.0042	0.0018	0.0034
min up time (h)	5	5	4	1
min down time(h)	4	3	2	1
Hot start cost(\$)	500	170	150	0
Cold start cost(\$)	1100	400	350	0.02
Cold start hrs(h)	5	5	4	0
Initial status(h)	8	8	-5	-6

1.1 Load demand for 8 hours.

Hour	1	2	3	4	5	6	7	8
Load (MW)	450	530	600	540	400	280	290	500

2. Input data for 10- generating units.

Data Description	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
P_i^{\max} (MW)	455	455	130	130	162
P_i^{\min} (MW)	150	150	20	20	25
a_i (\$/h)	1000	970	700	680	450
b_i (\$/MW h)	16.19	17.26	16.60	16.50	19.70
c_i (\$/MW ² h)	0.00048	0.00031	0.002	0.00211	0.00398
min up time (h)	8	8	5	5	6
min down time(h)	8	8	5	5	6

Hot start cost(\$)	4500	5000	550	560	900
Cold start cost(\$)	9000	10000	1100	1120	1800
Cold start hrs(h)	5	5	4	4	4
Initial status(h)	8	8	-5	-5	-6

2.1 Load demand for 24 hours.

Hour	Load (MW)	Hour	Load (MW)
1	700	13	1400
2	750	14	1300
3	850	15	1200
4	950	16	1050
5	1000	17	1000
6	1100	18	1100
7	1150	19	1200
8	1200	20	1400
9	1300	21	1300
10	1400	22	1100
11	1450	23	900
12	1500	24	800

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