EMISSION CONSTRAINED THERMAL UNIT COMMITMENT USING DIFFERENTIAL EVOLUTION

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CERTIFICATE

I hereby certify that the work which is being presented in Dissertation entitled, **"EMISSION CONSTRAINED THERMAL UNIT COMMITMENT USING DIFFERENTIAL EVOLUTION",** in partial fulfilment of requirement 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 embodies in this dissertation has not been submitted for the award of any other degree to any other university.

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ABSTRACT

Unit commitment problem (UCP) is a nonlinear mixed integer optimization problem to schedule the operation of the generating units at minimum operating cost while satisfying the demand and other equality and inequality constrains. The UCP has to determine the on/off state of the generating units at each hour of the planning period and optimally dispatch the load and reserve among the committed units. Unit Commitment is the most significant optimization task in the operation of the power systems.

During the last few years, emission control has become a problem of global concern due to the constantly increasing pollution of earth’s atmosphere. In order to reach the emission reduction targets imposed by the Kyoto Protocol, a limitation of the emissions produced by the generating units is needed. In this dissertation work Differential Evolution (DE) has been applied for the incorporation of the emission constraints in the solution of the thermal unit commitment problem. DE is simple but powerful and straightforward method for solving global optimization problems .The emission constraints are taken into account by integrating the cost of purchasing additional emission allowances, whenever the total system emissions exceed a predefined maximum limit, into the objective function of the unit commitment problem. Numerical simulations have proven the efficiency of the DE method.

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CHAPTER-1

INTRODUCTION

1.1 Introduction

The unit commitment problem (UCP) in power systems refers to the optimization problem for determining the start-up and shut-down schedule of generating units over a scheduling period so that the total production cost is minimized while satisfying several of constraints. Mathematically, the UCP has commonly been formulated as a complex nonlinear, mixed-integer combinational optimization problem with 0–1 variables that represents on-off status and continuous variables that represents unit power and a series of prevailing equality and inequality constraints. Unit commitment (UC) is a mixed-integer combinatorial optimization problem in a power system that involves determining a start-up and shut down schedule of the generating units to meet the hourly varying projected system demand. For each hour of a day, units are to be selected, satisfying various constraints such that the cost of supplying the load is minimum [1].

Two types of variables are associated with each unit-

(1) One to represent the selection of a generating unit.

(2) The other to represent the output of active powers of the units.

The first variable to represent the selection is binary in nature, and the second one representing the power output is real. The power output of a unit is known by solving the economic load-dispatch problem .Therefore, the aim of the UC problem is to properly schedule the on-off state of all the units supporting both variables in the system. The resulting schedule should minimize the system production cost during the period while simultaneously satisfying the load demand, spinning reserve, and physical operational constraints of the individual unit [1].

1.2 Literature Review

Different method for solution of unit commitment problem (UCP) can be of three types-

(1) Classical Method

(2) Random Search Techniques

(3 Hybrid Techniques

Priority list method is simplest of the unit commitment solution methods. It consist of creating a priority list of units .Priority listing method initially arranges the generating units based on lowest operational cost characteristics .The pre-determined order is then used to commit the units such that the system load is satisfied. F.N. Lee, *et al.* [2] introduced approach for determining the priority order for thermal unit commitment. In this approach index commitment utilization factor is used in conjunction with the classical economic index average full-load cost to determine the priority commitment order. F.N. Lee, *et al.* [3] introduced a technique for a thermal unit commitment method for interconnected multi-area power systems. The method is extension of commitment utilization factor based single-area unit commitment method. The commitment utilization factor based multi-area unit commitment method is used to generate the multi-area priority commitment order for varying transmission capacity. T.Senjyu, *et al.* [4] introduced extended priority list method. The approach consists of two steps. The initial UC schedules are produced by priority list method and then modified using the problem specific heuristics to fulfill unit and system constraints. The Economic Dispatch is performed only on the feasible schedules. T.Senjyu, *et al.* [5] introduced Stochastic Priority List method. The initial feasible UC schedules are generated by Priority List method and priority based stochastic window system. The heuristics are used to reduce search space and computational time.

Dynamic programming (DP) searches the solution space that consists of the unit status for an optimal solution .The search can proceed in a forward and backward direction. The time periods of the study horizon are known as the stages of the DP program. Typically each stage represents one hour of operation. The combinations of units within a time period are known as the stages of the DP problem. P. G. Lowery, [6] solved practical applicability of DP for solving UCP. The main concern was to determine the feasibility of using DP to solve the UCP. H.H. Happ, *et al.* [7] discussed the elapsed computing time required to perform the commitment function in a process computer while executing higher priority function is small over manual methods of commitment. C.K. Pang, *et al.* [8] compared the performance of four UC methods, three of which are based on the DP approach. G. L Kusic, *et al*. [9] solved the UC of wholly owned and commonly owned units. Each owner receives power from the commonly owned unit through tie lines with the operating owner. The DP algorithm generates all valid combinations of generating units, including wholly owned units and shares of commonly owned unit's with a must-run status. W.L.Synder, *et al.* [10] introduced a DP algorithm for UC problem. This algorithm incorporates a number of special features and effectively deals with the control of problem size. The discussion includes practical considerations and design techniques.

W.J.Hobbs, *et al.* [11] introduced an enhanced DP approach for UC. This method not only supports realistic modeling of unit start-up ramps, it involves the analysis of solution paths that may have been eliminated under traditional methods, thereby making possible better solutions. C.C.Su, *et al.* [12] introduced a dynamic security constrained multi-area UC. The goal of the presented approach is to achieve a multi-area generation schedule which not only meets the conventional requirements of having lowest fuel costs with the spinning reserves and steady-state transmission capacity limits satisfied, but also offers good dynamic performance through the enforcement of dynamic security constraint. C.Li, *et al.* [13] introduced a UC method based on decommitment procedure for solving the power resource scheduling problem. From an initial schedule of all available units committed over the Study period, one at a time unit decommitment is accomplished by DP. The UC method based on the decommitment procedure provides a powerful tool for solving the power system resource scheduling problem. D.P.Kothari, *et al.* [14] solved the multi area UC problem using truncated DP and applied to Indian power system with two different areas having different operating characteristics. T.K.Siu, *et al.* [15] developed a practical hydro dynamic UC and loading model for the British Columbia Hydro Power Authority. The problem is formulated and solved with a novel procedure that incorporates three algorithms. First, an expert system is used to eliminate infeasible and undesirable solutions. Second, DP is used to solve the optimal static UCP for a given plant loading, feasible unit combinations, and current hydraulic conditions. Third, the DUCL problem is formulated and solved as a large-scale network problem with side constraints**.**

The mixed-integer programming (MIP) approach solves the UC problem by reducing the solution search space systematically through discarding the infeasible subsets. The general solution concept is based on solving a linear program and checking for Integer solution .If the solution is not integer, linear problems are continuously solved. Integer programming optimizes integer function of integer variables. A modification of standard integer programming that allows non-integer function is known as MIP. Mixed integer Programming (MIP) treats the objective and constraint function as continuous and the variables as integers. Branch and bound is one of the techniques used for the solution of the integer problem**.** T. S. Dillon, *et al.* [16] introduced an integer programming approach to the problem of optimal UC with probabilistic reserve determination. An extended and modified version of branch and bound technique is used for Integer Programming and treats the commitments of both hydro and thermal systems. S.D.Bond, *et al.* [17] introduced optimal thermal unit scheduling using improved DP algorithm. In this method MIP is used to determine feasible combinations of units at each scheduling point, while a novel DP identifies promising scheduling routes in the time domain. S.K.Tong, *et al.* [18] introduced a technique for determining the UC schedule of a power system which operates under fuel utilization constraints. The proposed method employs the LR approach to determine a feasible suboptimal schedule. S. Takriti, *et al*. [19] presented a technique for refining the schedules obtained by LR method. Given the schedules generated by LR iterations, and improved schedule was found by solving the MIP. The model was an integer program with non linear constraints and solved for optimal solution using branch and bound technique. The method gives a significant improvement in terms of quality of the solution for large number of units. Li Tao, *et al*. [20] formulated the price-based UC problem based on the MIP method. The proposed price-based UC solution is for a generating company having cascaded-hydro, thermal, pumps storage and combined-cycle, units. The results are compared with LR method.

The Lagrangian Relaxation (LR) optimization technique decomposes the UC problem in to a master problem and more manageable sub problems that are solved iteratively until a near optimal solution is obtained. A. Merlin, *et al.* [21] introduced implementation in solving UCP by LR method. Numerous developments were envisaged, to make the algorithm flexible such as simultaneous management of pumping units, probabilistic determination of the spinning reserve. This decomposition method used is flexible and Lagrange multiplier provides a solution to the conventional problem. R.Nieva, *et al.* [22] introduced an approach to solve very large and complex UCP. The approach gives an estimate of sub optimality that indicates the closeness of the solution near to the optimum. K.Aoki, *et al*. [23] presented an LR method for UC in large scale power systems, which includes three types of units such as usual thermal units, fuel constrained thermal units, and pumped storage hydro unit. F. Zhuang, *et al.* [24] formulated an LR method for large scale problem. The algorithm in divided into three phases. First the Lagrangian dual of the UC is maximized with standard sub gradient techniques, second a reserve-feasible dual solution is obtained and finally ED is performed. R.Baldick, *et al.* [25] formulated UCP in generalized form and solved using LR method. The algorithm, presented, approximately solves the dual optimization problem. H.Ma *,et al* .[26] introduced optimal power flow in the UC formulation using benders decomposition, the formulation is decomposed into a master problem and a sub problem. The master problem solves UC with prevailing constraints, except transmission security and voltage constraints by augmented LR.

The branch-and-bound method consists of upper bound on the minimum value of the objective function and Convergence takes place when only one subset of decision variables remains, and the upper and lower bounds are equal for that subset. G.S.Lauer, *et al.*[27] introduced a approach for solving large scale optimal UC problem using branch and bound method, which incorporates minimum up and down time constraints, demand and system reserve constraints, cooling-time dependent startup-costs, and time varying shut down costs. A.I.Cohen, *et al.* [28] introduced a branch and bound algorithm for UC. It does not require a priority ordering of the units. The decision variables are the start and stop times and the generation levels of the units. K.Y.Huang, *et al.* [29] introduced a constraint logic programming along with the branch-and-bound technique to provide an efficient and flexible approach to the UC problem. The combined use of the constraint satisfaction techniques and the B&B optimization strategy is devoted to reducing the search space very efficiently by actively exploiting the constraints.

Tabu search (TS) is a powerful optimization procedure that has been successfully applied to a number of combinatorial optimization problems. It has the ability to avoid entrapment in local minima by employing a flexible memory system. H. Mori, *et al.*[30] introduced a method for UC using TS with the restricted neighborhood of the solution search .In this method the restricted neighborhood of solution search is investigated to improve the performance in TS. A.H. Mantawy, *et al.* [31] introduced an integrating GA, TS and SA for the UC problem. The core of the proposed algorithm is based on GA. Tabu search is used to generate new population members in the reproduction phase of the GA. Simulated annealing method is used to accelerate the convergence of the GA by applying the SA test for all the population members. H. Mori, *et al.* [32] introduced the priority list method with TS for UC. The method is based on the TS that embed the priority list of units into the neighborhood to reduce computational time while keeping better solution accuracy. The problem is decomposed into two phases. One handles on-off conditions of generators with TS while the other determines output variables of generators using the equal lambda method. A.Rajan, *et al.*[33] solved the short-term UCP using Neural Based TS. The algorithm is based on the short - term memory procedure of the TS method. TS are characterized by its ability to escape local optima by using a short term memory of recent moves. TS permits back tracking to previous solutions for getting better solutions.

In Simulated Annealing (SA) method the UC problem has been compared to the annealing of a metal. When the metal is cooled slowly, its energy tends to assume a globally minimal value. The states of a metal correspond to the various feasible solutions of the problem to minimize and the energy of states is analogous to the cost of a feasible solution. Simulated annealing generates near optimal and fast solution. F.Zhuang, *et al.* [34] introduced unit commitment using SA. Simulated Annealing generates feasible solutions randomly and moves among these solutions using a strategy leading to a global minimum with high probabilities. This method is highly flexible in handling unit commitment constraints. U.D.Annakkage, *et al.* [35] introduced a Parallel SA algorithm for UCP. Two conventional parallel SA algorithms speculative computation and serial subset have been combined together.

Expert system (ES) is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solutions. Expert systems combine the identification of existing problems with the UC algorithms and the knowledge of experienced power system operators and UC programming experts to create an expert system rule base. M.S.Salem, *et al.* [36] has developed an expert system for thermal UCP. The ES is used as a preprocessor as well as a postprocessor to the truncated DP based UC program to obtain an operationally feasible and preferable solution. S. Li, *et al.* [37] introduced a heuristic approach to the short-term UCP. Expert system-based approach to short-term UCP, which is intended to process large generating schedules in real time, which combines database management with the latest developments in expert system design and extensive use of man machine interfaces are used for this investigation. S.Mukhtari, *et al.* [38] introduced an ES for scheduling the operation of generating units. First, problems with existing UC algorithms were identified. Then the knowledge of an experienced power system operator and a UC programming expert were combined to create an expert system rule base. S.K.Tong, *et al.* [39] introduced hydrothermal UC problem with probabilistic constraints using segmentation method. This approach provides a rational modeling of the problem by considering the outages of thermal units and the uncertainty of the demand. Thermal UC is optimized by using DP. Z.Ouyang, *et al.* [40] proposed a multi–stage intelligent system for UCP. The proposed short term UC employs a multi-stage neural network-expert system approach to achieve real time processing results. The operating constraints are presented as heuristic rules in the system where a feasible solution is obtained through inference. The neural networks are used at the pre-processor and post-processor stages.

Artificial neural networks (ANNs) are intended to model the behavior of biological neural networks. The original hope for the development of ANNs is intended to take advantage of parallel processors computing than traditional serial computation. Several models of ANNs and the learning algorithms that are associated with networks have been developed. N. Chowdhury, *et al.* [41] introduced UCP in interconnected generating systems using a probabilistic technique. The technique is developed on the basis of each area in a multi-area configuration fulfilling two different risk criteria. H.Sasaki, *et al.* [42] introduced a solution method of UCP using artificial neural networks. In this method generators to start up at each period are determined by the network and then their outputs are adjusted by a conventional algorithm. C.Wang, *et al.* [43] introduced an approach for incorporating unit ramp-rate limit in UCP and economic dispatch problem. The basic idea in this method is to utilize the optimal information obtained by the traditional methods which do not include the ramping limits, and use dynamic adjusting procedures to incorporate ramping constraints. ANN and a heuristic method are adopted to generate the optimal UC schedule for a given load curve. S.Saneifard, *et al.* [44] introduced the fuzzy logic to UCP. This method allows a qualitative description of the behavior of a system, the system characteristics, and response without the need for exact mathematical formulations. M. P. Walsh, *et al.* [45] introduced Augmented Hopfield Network for UCP and Economic Dispatch problem. In this method augmented network architecture with a new form of interconnection between neurons giving a more general energy function containing both discrete and continuous terms. A comprehensive cost function for the UCP is developed and mapped to this energy function. R.H.Liang, *et al.* [46] introduced thermal generating UCP using an extended mean field annealing neural network approach. The annealing neural network combines good solution quality for SA with rapid convergence for artificial neural network.

D. Dasgupta, *et al.* [47] introduced a genetic algorithm (GA) approach for determining the priority order in the commitment of thermal units in power generation. The GA based UC system evaluates the priority of the units dynamically considering the system parameters, operating constraints and load profile at each time period in the scheduling horizon. X. Ma, *et al.* [48] introduced a GA based approach to UCP and economic dispatch problem. The advantage of this GA based UCP lies in its ability to handle ill-structured nonlinear optimization problems. P.C.Yang, *et al.* [49] introduced an innovative GA approach to solve the thermal UCP in power generation industry through a constraint satisfaction technique. To effectively deal with the constraints of the problem and greatly reduce the search space of the GA, the minimum up- and down-time constraints are embedded in the binary strings that are coded to represent the on-off states of the generating units. The violations of the other constraints are handled by integrating penalty factors into the cost function. P.C.Yang, *et al.* [50] introduced a parallel GA approach to solve the thermal UCP in power generation industry through a constraint satisfaction technique. Minimum up-time and down-time constraints on the generating units are embedded in the delicately designed binary strings to represent the on-off states of the units. Ramp rate constraints on the units being started up or shut down are tackled in the economic dispatch sub program by limiting the associated maximum available capacities for generating units. S.O. Orero, *et al.* [51] introduced a GA for short term optimal hydrothermal scheduling. A multi-reservoir cascaded hydro-electric system with a non-linear relationship between water discharge rate, net head and power generation is considered. The water transport delay between connected reservoirs is also taken into account. H.T.Yang, *et al.* [52] introduced an Evolutionary Programming (EP) based economic dispatch for units with non smooth fuel cost functions. The EP algorithm is capable of determining the global or near global optimal dispatch solutions in the cases where the classical Lagrange based algorithms cease to be applicable. K.A.Juste, *et al.* [53] introduced an EP solution to the UCP in which populations of contending solutions are evolved through random changes, competition, and selection.

S.J.Huang, *et al.* [54] introduced an Ant Colony System (ACS) based optimization approach is for the enhancement of hydroelectric generation scheduling. The search space of multi-stage scheduling is first determined through a collection of cooperative agents called ants. M. Y. El-Sharkh, *et al.* [55] introduced an improved ACSA for UCP. The ACSA was inspired by the behavior of real ants that are capable of finding the shortest path from food sources to the nest without using visual cues. The constraints used in the solution of the UC problem using this approach are real power balance, real power operating limits of generating units, spinning reserve, start up cost, and minimum up and down time constraints.

Particle swarm optimization (PSO) first introduced by Kennedy and Eberhart is one of the heuristic optimization algorithms. A classical PSO maintains a swarm of particles that represent the potential solutions to the problem on hand. The classical PSO model consists of a swarm of particles moving in the D-dimensional space of possible problem solutions. Each particle embeds the relevant information regarding the D decision variables and is associated with a fitness that provides an indication of its performance in the objective space. Z.L.Gaing, *et al.* [56] introduced binary PSO for solving the UCP. The economic sub problem is solved using the lambda iteration method for obtaining the total production cost. B. Zhao, *et al.* [57] Introduced an improved PSO algorithm for UC which utilizes more particles information to control the process of mutation operation. X. Yuan, *et al.* [58] introduced improved binary PSO for solving UCP. The standard PSO is improved the using the priority list and heuristic search to improve the MUT and MDT constraints.

Main objective of hybrid techniques is to overcome the limitations of classical, ES and fuzzy decision system approach, while determining the unit commitment schedule of generating units. The objective of hybrid of two or more methods is to speed up the convergence and to get better quality of solution compared with single approaches. C.C.Su, *et al.* [59] introduced a fuzzy DP for UCP. A characteristic feature of the presented approach is that the errors in the forecasted hourly loads can be taken into account by using fuzzy set notations, making the approach superior to the conventional DP method. Z. Ouyang, *et al.* [60] utilized neural networks to generate a pre-schedule according to the forecasted load curve. D. P. Kothari, *et al.* [61] described a hybrid expert system DP approach. The output scheduling of the usual DP is enhanced by supplementing it with the rule based expert system. H. Shyh-Jier, *et al.* [62] introduced GA based neural network and DP approach for UCP. At the initial stage a set of feasible UC schedules are generated by genetic-enhanced neural networks. In the second stage these schedules are optimized by using the DP approach. C. P. Cheng, *et al.* [63] introduced an application of GA and LR method for solving the UCP. The proposed approach incorporates GA into LR method to improve the performance of LR and to update the Lagrangian multipliers.

C. C. A. Rajan, *et al.* [64] introduced a neural based TS method for solving UCP. The algorithm is based on the short term memory procedure of the TS method. A.Y.Saber, *et al.* [65] introduced a two-fold SA method for solving UCP. A hybrid of SA and fuzzy logic is used to obtain SA probabilities from fuzzy membership function. The initial feasible UC schedules are generated by a priority list method and are modified by de-composed SA using a bit flipping operator. N.Sadati, *et al.* [66] introduced hybrid PSO based SA approach for solving UCP. The unit scheduling of sub problem is solved by using binary PSO and economic dispatch sub problem is solved by using real valued PSO. S. S. Kumara, *et al.* [67] introduced DP based direct Hopfield computation method. The proposed approach solves the UCP in two steps. The generator scheduling problem is solved using DP and generation scheduling problem is solved using Hopfield neural network.

Differential evolution (DE) developed by Rainer Storn and Kenneth Price in 1995 who shown that DE is a powerful tool to optimize real-valued multimodal objective functions [68]. Differential evolution (DE) is similar to GA but differs from GA with respect to the mechanism of how mutation, crossover and selections are performed. Differential evolution (DE) has seen growing popularity as an effective yet simple evolutionary algorithm. Its main feature is that the difference between population members is used for the mutation process instead of randomly generated values. Its ease of use and implementation make it a more attractive approach to evolutionary algorithms. C.J.Wu, *et al.* [69] introduced design of decentralized output feedback power system stabilizers using hybrid DE. G.A.Bakare, *et al*. [70] introduced DE approach for reactive power optimization of Nigerian grid system. The goal of reactive power dispatch is to minimize the system losses and improve the system voltage profiles at all times. M.C.Ai, *et al*. [71] introduced Improved DE algorithm application in induction motor speed control. The algorithm is to convert equations into an optimization problem and by keeping consideration of the evolution process and adopting dynamic parameters adjusting mechanism. C. M. Selvi, *et al.* [72] introduced power system voltage stability analysis using modified DE. In this approach, the margin from the current operating point to the maximum loading point of the system is determined. Finding this maximum loading point can be formulated as an optimization problem.

G.I.Rashed, *et al.*[73] introduced optimal Thyristor Controlled Series Compensator (TCSC) placement in a power system by means of DE algorithm considering loss minimization. Differential Evolution (DE) is used to select the optimal location and the optimal parameter setting of TCSC which minimize the active power losses in the power network. G.I.Rashed, *et al*. [74] introduced optimal placement of TCSC in power system based on DE algorithm. Differential Evolution (DE) is used for finding out the optimal number, the optimal locations, and the optimal parameter settings of multiple TCSC devices to achieve maximum system load ability in the system with minimum installation cost of this device. C.M.Huang, *et al*. [75] introduced optimal active-reactive power dispatch using an enhanced DE algorithm. A DE algorithm enhanced by combining variable scaling mutation and ant algorithm was proposed to alternatively solve the active-reactive power dispatch problem in a single simulation run. C.L.Chiang, [76] introduced an improved DE based multi-objective approach for the optimal economic emission dispatch of the hydrothermal power system considering non-smooth fuel cost and emission level functions. M.Govardhan, *et al.* [77] introduced an application of DE technique on UCP using priority list approach.

1.3 Organization of the Dissertation

Dissertation titled as "*Emission Constrained Thermal Unit Commitment Using Differential Evolution*" is divided into six chapters. Chapter one provides the detailed introduction on unit commitment along with literature review pertaining to the problem. Chapter two describes the formulation of emission constrained thermal unit commitment problem. Chapter three deals with the explanation of DE technique and its algorithm. Chapter four presents the solution approach to the emission constrained thermal unit commitment problem using DE. Chapter five covers the discussion pertaining to results and chapters six summarize the conclusions and scope for further work.

CHAPTER-2

Emission Constrained Thermal Unit Commitment

2.1 Introduction

Unit Commitment (UC) is essential in the present competitive and vibrant energy market, since a significant amount of savings can be obtained by a sound UC decision. UC is a process of determining the minimal production cost generator turn ON/turn OFF schedule and real power outputs of committed units while meeting the forecasted demand over a scheduling horizon of usually between 24hrs to 168hrs (1 day-7 days) [1].

One of the main contributions to the emission of greenhouse gases into the atmosphere, which is thought to be responsible for climate change on our environment, is through the use of fossil-fuelled power plants. In emission constraints unit commitment problem the total production cost is minimized while satisfying several of constraints along with maximum emission limit of generating units. The major aim of the emission constraint is to restrict the emission of carbon di oxide (CO_2), silicon di oxide (SO_2) and Nitrogen oxides (NOx) of the thermal generating units [78].

The introduction of emission constraint has made the UC problem a more complex one. The combinatorial nature of UC has curtailed any attempt to develop a rigorous mathematical optimization method. The optimal solution is assured, if complete enumeration is carried out on all possible combinations. But it is not suitable for large scaled real sized system since it involves excessive computational complexity.

2.2 Constraints in Unit Commitment

2.2.1 Unit Type

The thermal units are usually divided into the following unit types-

(1) Must-run units

(2) Cycling units

(3) Peak load unit.

Must-run units are those units that must be on-line, if available, due to operating constraints, reliability requirements, or economic considerations. In power system some of the units are given a must run status in order to provide voltage support for the network. Cycling units are units that can cycle on and off and are subject to minimum up and down-time constraints. Peak load units are those generating units which are capable to serve the load demand in case of any sudden increase in load demand and these are able to start up in less possible time, usually gas turbines generating unit serves the motive of peak load units [1].

2.2.2 Spinning Reserve

The spinning reserve is the most important resource used by power system operators to respond to sudden generation outages and prevent load disconnections. While its availability has a substantial value because it mitigates the considerable social and economic costs of occasional outages, the continuous provision of spinning reserve is costly because additional generating units must be committed and some generating units must be operated at less than optimal output. Power system operators usually set the spinning reserve based on criteria that guarantee that the power system will operate with an acceptable level of risk .This spinning reserve is required to compensate for sudden generating units outages and sudden load increase. [8].

2.2.3 Thermal Unit Constraints

The temperature and pressure of the thermal units vary very gradually and units must be synchronized before they are brought online. Thermal units usually require a crew to operate them, especially when turned on and turned off. A thermal unit can undergo only gradual temperature changes, which in turn translates into a time period of some hours that are required to bring the unit online [8].

2.2.3.1 Minimum up time:

Once the unit is running, it cannot be turned off immediately. It means that generating unit cannot turn off immediately; it needs some time to reach the off state.

$$T_{i,t}^{on} \geq MUT_i \qquad (2.1)$$

where $T_{i,t}^{on}$ = continuously on time duration for i^{th} unit upto time *t*

MUT_i = Minimum up-time for i^{th} unit

2.2.3.2 Minimum down time:

Once the unit is decommitted, there is a minimum time before it can be recommitted. It means that generating unit cannot turn on immediately; it needs some time to reach the committed state.

$$T_{i,t}^{off} \geq MDT_i \qquad (2.2)$$

where $T_{i,t}^{off}$= continuously off time duration for i^{th} unit upto time *t*

MDT_i = Minimum down-time for i^{th} unit

2.2.4 Crew constraints

If a plant consists of two or more units, they cannot both be turned on at the same time since there are not enough crew members to attend both units at the start up. In addition, a certain amount of energy must be expended to bring the unit online as the temperature and pressure of the thermal unit are required to move slowly, this energy does not result in any MW generation from the unit and is brought into the unit commitment problem as a start-up cost. The start-up cost can vary from a maximum cold-start value to a much smaller value.

If the unit was only turned off recently and is still relatively close to operating temperature. Then the unit's boiler will cool down and then heat back, it up to the operating temperature, in time for a scheduled turns on [1].

Start up cost when cooling is given by

$$C_c\left(1 - e^{\frac{t}{\alpha}}\right) \times F + C_f \quad (2.3)$$

where C_c=cold-start cost

C_f=fixed cost (includes crew expense, maintenance expenses)

F =fuel cost

α =thermal time constant for the unit

t =time (h) the unit was cooled

Due to maintenance or unscheduled outages of various equipment in the plant the capacity limits of thermal units may change frequently; this must also be taken into account in unit commitment.

2.3 Formulation of Emission Constraint Thermal Unit Commitment

2.3.1 Objective Function

The main objective of the emission constraint UC problem is to minimize the total operating cost of generating units by keeping the emission limit of units under its maximum limit during the scheduling horizon, subject to a number of system and unit constraints. The overall objective function of the UC problem is expressed as the sum of fuel, start-up, and shut-down costs of generating units [78].

2.3.1.1 Fuel Cost Function

For all committed generating units, the total fuel cost is minimized by economically dispatching the units. The fuel cost function of unit i at hour t is expressed as a second order polynomial as follows:

$$F_i(P_{i,t}) = a_i + b_i P_{i,t} + c_i P_{i,t}^2 \tag{2.4}$$

where $P_{i,t}$ = Power generated by unit i at hour t

a_i, b_i, c_i = The cost coefficients of unit i

2.3.1.2 Emission Function

The emission (kg/hr) of the generating units is given by the quadratic equation:

$$E_i(P_{i,t}) = \alpha_i + \beta_i P_{i,t} + \gamma_i P_{i,t}^2 \tag{2.5}$$

where $P_{i,t}$ = Power generated by unit i at hour t

$\alpha_i, \beta_i, \gamma_i$ = The emission coefficients of unit i

2.3.1.3 Start-Up Costs

Start-up costs for restarting a decommitted thermal unit, which is related to the temperature of the boiler, is included in the model. That is, the start-up cost depends on the number of hours during which the unit has been off. Start-up costs will be hot start up cost ($F_{hs,i}$) when down time duration exceeds the cold start hour ($T_{cold,i}$) in excess of minimum down time and will be cold start up cost ($F_{cs,i}$) when down time duration does not exceed the cold start hour in excess of minimum down times. In general, the start-up cost is described in the two-step function as follows:

$$SC_{i,t} = \begin{cases} F_{hs,i} & if\ MDT_i \le T_{i,t-1}^{off} \le MDT_i + T_{cold,i} \\ F_{cs,i} & if\ T_{i,t-1}^{off} > MDT_i + T_{cold,i} \end{cases} \tag{2.6}$$

where $T_{i,t}^{off}$ = the duration for which unit i is continuously off-line at hour t

$SC_{i,t}$ = Start-Up Costs of i^{th} unit at time t

MDT_i= the minimum down-time of unit i

$F_{hs,i}$ =Hot start up cost for i^{th} unit

$F_{cs,i}$ =Cold start up cost for i^{th} unit

$T_{cold,i}$ = Cold start up time for i^{th} unit

2.3.1.4 Shut-Down Costs

Shut-down costs are usually modeled as a constant value for each unit per shut down. The shut down costs have been taken as equal to 0 for all units and is excluded from the objective function.

Consequently, the UC objective function is given by the minimization of the following cost function [78]:

$$OC_T = \sum_{t=1}^{T}\sum_{i=1}^{N}[F_i(P_{i,t}) + \mu \times E_i(P_{i,t})] \times U_{i,t} + [SC_{i,t} \times (1 - U_{i,t-1}) \times U_{i,t}] \quad (2.7)$$

where OC_T =Total operating costs for the scheduling period

$SC_{i,t}$ = Start-Up Costs of i^{th} unit at time t

N =No. of units

T=Scheduling period

$P_{i,t}$ = Power generated by unit i at hour t

$F_i(P_{i,t})$ =Production cost of i^{th} unit at time t

$U_{i,t}$ = Binary variable to indicate the on/off state of i^{th} unit at time t

$$U_{i,t} = \begin{cases} 1 & if\ i^{th}\ unit\ is\ online \\ 0 & if\ \ i^{th}\ unit\ is\ offline \end{cases}$$

2.3.2 System Constraints:-

There are two types of constraints in TUCP.

1) Equality constraints
2) Inequality constraints

2.3.2.1 Equality Constraints

Power Balance Constraint

The sum of the unit generation output at each hour must satisfy the system load demand requirement of the corresponding hour as follows:

$$\sum_{i=1}^{N} P_{i,t} \times U_{i,t} = P_{d,t} \quad (2.8)$$

where $P_{d,t}$= Total power demand at hour t

$P_{i,t}$ = Power generated by unit i at hour t

$U_{i,t}$ = Binary variable to indicate the on/off state of i^{th} unit at time t

2.3.2.2 Inequality Constraints

Emission Constraints

The emission of the unit is under its maximum limit.

$$\sum_{t=1}^{T}\sum_{i=1}^{N} E_i U_{i,t} \leq E_i^{max} \tag{2.9}$$

where E_i = Emission from a unit

E_i^{max} = Maximum emission of the i^{th} unit

$U_{i,t}$ = Binary variable to indicate the on/off state of i^{th} unit at time t

Spinning Reserve Constraints

Spinning reserves must be available during the operation of a power system in order to minimize the probability of load interruption. The reserve is considered to be a pre-specified amount or a given percentage of the forecasted peak demand. Spinning reserves can be specified in terms of excess megawatt capacity, which is expressed by:

$$\sum_{i=1}^{N} P_i^{max} \times U_{i,t} \geq P_{d,t} + R_t \tag{2.10}$$

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

R_t = Spinning reserve power at time t

Generations Limit Constraints

The power produced by each unit must be within certain limits, as indicated below:

$$U_{i,t} \times P_i^{min} \leq P_{i,t} \leq U_{i,t} \times P_i^{max} \tag{2.11}$$

where P_i^{min}, P_i^{max} the minimum and maximum generations are limits of unit i respectively.

Minimum Up-Time Constraints

A unit must be on for a certain number of hours before it can be shut down.

$$T_{i,t}^{on} \geq MUT_i \tag{2.12}$$

where $T_{i,t}^{on}$ = Continuously on time duration for i^{th} unit up to time t

MUT_i = Minimum up-time for i^{th} unit

Minimum Down-Time Constraints

A unit must be off for a certain number of hours before it can be brought online.

$$T_{i,t}^{off} \geq MDT_i \tag{2.13}$$

where $T_{i,t}^{off}$ = Continuously off time duration for i^{th} unit up to time t

MDT_i =Minimum down-time for i^{th} unit

Unit initial status

The initial unit states at the start of the scheduling period must be taken into account.

CHAPTER 3

DIFFERENTIAL EVOLUTION

3.1 Introduction

A random search technique leads to the global optimization inspired by Darwinian evolution of species came in to existence i.e. Differential Evolution proposed by R.Storn and K.V.Price in 1995 [68]. Differential evolution (DE) is arguably one of the most powerful stochastic real-parameter optimization algorithms in current use. Differential evolution (DE) operates through similar computational steps as employed by a standard evolutionary algorithm (EA).The DE-variants perturb the current generation population members with the scaled difference of randomly selected and distinct population members. Therefore, no separate probability distribution has to be used for generating the offspring.

DE is used for multi dimensional real-valued functions but does not use the gradient of the problem being optimized. DE does not require for the optimization problem to be differentiable as is required by classic optimization methods such as gradient descent and quasi-newton methods. DE can therefore also be used on optimization problems that are not even continuous.

3.2 Overview of Differential Evolution (DE)

Differential Evolution (DE) is an evolutionary algorithm based on the populations of possible candidate solutions with three operators: mutation, crossover and selection. In DE candidate solutions are identified by vectors and set of vectors generate the population. The basic notion is to form new vector by means of the weighted difference between the two population vectors. These three vectors are chosen randomly. Then the fitness of new vector is checked. If the fitness of the last vector is better than the previous two, then the exchange takes place.

The performance of DE is heavily dependent on the setting of control parameters. Proper selection of control parameters is very important for the success of the algorithm. An optimal setting of control parameters of differential evolution depends on the specific problem under consideration**.**

3.2.1 Initialization

The basic step in DE optimization is to create an initial population of candidate solutions by assigning random values to each decision parameter of each individual of the population [68]**.** A population P consisting of N_P individuals is constructed in a random manner such that the values lie within the feasible bounds P_j^{min} and P_j^{max} of the decision variable, according to the following rule:

$$P_{i,j} = P_j^{min} + rand \times \left(P_j^{max} - P_j^{min}\right) \quad (3.1)$$

Where i= 1, 2,..…, N_P Denotes the individual's population index

j=1, 2,….,D Signifies the D-dimensional search space position

P_j^{min} =Lower bound of the decision variable

P_j^{max} =Upper bound of the decision variable

$rand$= An uniformly distributed random number varies between 0 to 1

3.2.2 Mutation

Next generation offspring are introduced into the population through the mutation process. Mutation is performed by choosing three individuals from the population P_{new} in a random manner [68].

Let P_{ra}, P_{rb} ,P_{rc} represent three random individuals such that $ra \neq rb \neq rc \neq i$ upon which mutation is performed during the G^{th} generation as:

$$V_i^{(G+1)} = P_{ra}^{(G)} + fm \times \left(P_{rb}^{(G)} - P_{rc}^{(G)}\right) \quad (3.2)$$

3.2.3 Crossover

New offspring members are reproduced through the crossover operation based on binomial distribution. The members of the current population (target vector) $X_{i,j}^{G}$ and the members of the mutated individual $V_{i,j}^{(G+1)}$ are subjected to crossover operation thus producing a trial vector $U_{i,j}^{(G+1)}$ according to following rule [68]:

$$U_{i,j}^{G+1} = \begin{cases} V_{i,j}^{G+1} & , if\ rand[0,1] \leq C_r \\ P_{i,j}^{G+1}, & otherwise \end{cases} \quad (3.3)$$

Where C_r is the crossover constant that controls the diversity of the population and prevents the algorithm from getting trapped into the local optima. The crossover constant must be in the range of [0, 1].

3.2.4 Selection

Selection procedure is performed with the trial vector and the target vector to choose the best set of individuals for the next generation. In this proposed approach, only one population set is maintained and hence the best individuals replace the target individuals in the current population. The objective values of the trial vector and the target vector are evaluated and compared. If the trial vector has better value, the target vector is replaced with the trial vector as per the following rule [68]:

$$P_i^G = \begin{cases} U_i^{G+1}, if\ f(U_i^{G+1}) \le f(P_i^G) \\ P_i^G, \quad otherwise \end{cases} \tag{3.4}$$

3.3 ADVANTAGES OF DE

DE is simple but powerful and straightforward method for solving global optimization problems and has many advantages as compared to other heuristic optimization techniques, which are as follows [68]:

- DE has ability to handle non-differentiable, nonlinear, multimodal cost functions.
- DE is fast and simple with regard to application.
- DE algorithm requires few control parameters.
- DE algorithm has parallel processing nature and fast convergence.
- DE algorithm has the ability to find the optimal solution for a nonlinear constrained optimization problem with penalty functions.

3.4 Flow Chart of DE

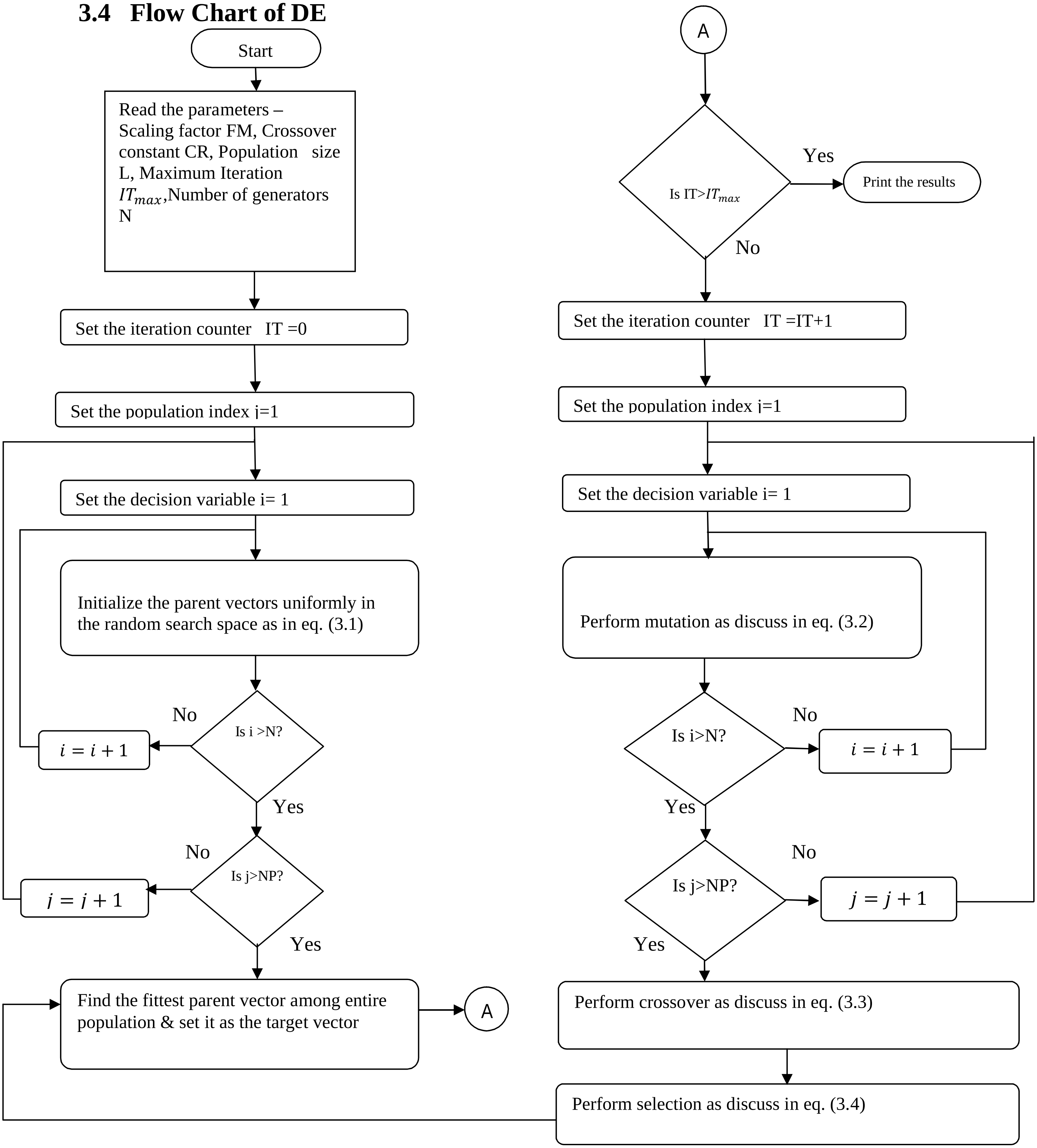

Fig. 3.1The flow chart of the DE

CHAPTER 4

EMISSION CONSTRAINED THERMAL UNIT COMMITMENT USING DIFFERENTIAL EVOLUTION

4.1 Introduction

Unit commitment problem (UCP) is a nonlinear mixed integer optimization problem to schedule the operation of the generating units at minimum operating cost while satisfying the demand and other equality and inequality constrains. The UCP has to determine the on/off state of the generating units at each hour of the planning period and optimally dispatch the load and reserve among the committed units. Unit Commitment is the most significant optimization task in the operation of the power systems. Solving the UCP for large power systems is computationally expensive. The complexity of the UC problems grows exponentially to the number of generating units [1].

Due to the environmental regulation enforced in recent years, emission control has also turned out to be a very important operation objective. The United Nations framework convention on climate change (UNFCCC) and its Kyoto Protocol provide an international framework for combating climate change [78]. The UNFCCC set out an obligation for all its signatory parties to establish national Programs for the reduction of greenhouse gases. Building on the UNFCCC framework, the Kyoto Protocol sets legally binding limits on greenhouse gas emissions in industrialized countries and envisages novel market-based mechanisms for achieving cost effective emission reduction.

Global warming presents the biggest threat to human living environment. Many countries have been or will be suffering from the problems caused by the rise of the sea level and extreme weather conditions. Among the factors accelerating global warming, the emission of green house gas such as carbon dioxide and methane, are the main contributing factors [79].

4.2 The Emission Constrained Problem

The objective of the emission constrained problem is the incorporation of the emission constraints in the formulation of the thermal UC problem. The enforcement of the above constraints is based on the presumption that the generating system is constrained by a predefined emission limit. This limit depends on the emission allowances which have been obtained by the examined system. Differential evolution (DE) method is used to evaluate the total generation cost and emission during a certain period. The method presented in this paper adds the emission objective to the unit-commitment problem. Units with high emission are committed fewer times than those with low emission. This results in a more economical operation than conventional methods, especially during higher load levels [78].

4.3 Calculation of Emissions

The power production by thermal power plants is always accompanied by the release of emissions in the form of CO_2, SO2 and NO_x. The emissions (kg/hr) produced by unit i at hour t can be calculated by the following equation [80]:

$$E_i(P_{i,t}) = (\alpha_i + \beta_i P_{i,t} + \gamma_i P_{i,t}^2) \tag{4.1}$$

where $P_{i,t}$ = Power generated by unit i at hour t

$\alpha_i, \beta_i, \gamma_i$ = The emission coefficients of unit i

4.4 Formulation of Emission Constrained Thermal Unit Commitment

4.4.1 Cost Function

The objective of the emission constrained thermal UC problem is to minimize the total operating costs while keeping the emission from the generating units under its maximum limit subjected to a set of system and unit constraints over the scheduling horizon. The total operating costs is the sum of the production costs and the start-up costs. The generator start-up cost depends on the time the unit has been switched-off prior to the start up. The start-up cost at any given time is assumed to be an exponential cost curve.

The economic dispatch may result in minimal cost but with higher emission, and the emission dispatch may yield a minimal emission and higher operating cost. To bring a balance between both emission and economic dispatch combined emission economic is used as the sub problem to dispatch the real power among the committed units obtained from the UC problem. The combined emission economic schedule is obtained by combining eqn. (2.4) & (2.5) [80].

The overall cost function is minimizing the total operating cost, subject to a number of system and unit constraints [1].

$$OC_T = \sum_{t=1}^{T} \sum_{i=1}^{N} [F_i(P_{i,t}) + \mu \times E_i(P_{i,t})] \times U_{i,t} + [SC_{i,t} \times (1 - U_{i,t-1}) \times U_{i,t}] \tag{4.2}$$

where

$$E_i(P_{i,t}) = (\alpha_i + \beta_i P_{i,t} + \gamma_i P_{i,t}^2) \tag{4.3}$$

$$F_i(P_{i,t}) = a_i + b_i P_{i,t} + c_i P_{i,t}^2 \tag{4.4}$$

and

$$SC_{i,t} = \begin{cases} F_{hs,i} & if\ MDT_i \le T_{i,t-1}^{off} \le MDT_i + T_{cold,i} \\ F_{cs,i} & if\ T_{i,t-1}^{off} > MDT_i + T_{cold,i} \end{cases} \tag{4.5}$$

4.4.2 Subjected to System Constraints

4.4.2.1 Emission Constraints

The emission of the unit is under its maximum limit.

$$\sum_{t=1}^{T}\sum_{i=1}^{N} E_i U_{i,t} \le E_i^{max} \tag{4.6}$$

The emission from a generating unit is compare with the maximum emission limit.

(1) If $E_i \le E_{max}$,the existing emission rights are sufficient to cover the emission of the trial solution.

(2) If $E_i > E_{max}$,an emission cost EMC is added to the total operating cost OC_T of the current solution.

The emission cost depends on the price EMP of the additional emission allowances which must be purchased.

$$EMC = \begin{cases} (E_{max} - E_i)\text{^}2\ \times EMP & ,if\ \ E_i > E_{max} \\ 0 & ,if\ \ \ E_i \le E_{max} \end{cases} \tag{4.7}$$

The above procedure allows the acceptance of the trial solutions which violate the emission constraint, considering the resulting increase in the total cost of the system. The final solution of the UC problem provides the optimal trade-off between the total cost of the system and the enforcement of the emission constraint. The price of the emission allowances determines whether it is more economical to exceed the system emission or not. The strict enforcement of the considered emission constraints can be achieved if a rather high value of EMP is chosen. The emission constrained method plays the role of a penalty function leading to solutions which are feasible with regard to the emission constraints [78].

4.4.2.2 Equality Constraints

Power Balance Constraint

The sum of the unit generation output at each hour must satisfy the system load demand requirement of the corresponding hour as follows:

$$\sum_{i=1}^{N} P_{i,t} \times U_{i,t} = P_{d,t} \tag{4.8}$$

4.4.2.3 Inequality Constraints

Spinning Reserve Constraints

Spinning reserves must be available during the operation of a power system in order to minimize the probability of load interruption. The reserve is considered to be a pre-specified amount or a given percentage of the forecasted peak demand. Spinning reserves can be specified in terms of excess megawatt capacity, which is expressed by:

$$\sum_{i=1}^{N} P_i^{max} \times U_{i,t} \geq P_{d,t} + R_t \tag{4.9}$$

Generations Limit Constraints

The power produced by each unit must be within certain limits, as indicated below:

$$U_{i,t} \times P_i^{min} \leq P_{i,t} \leq U_{i,t} \times P_i^{max} \tag{4.10}$$

Minimum Up-Time Constraints

A unit must be on for a certain number of hours before it can be shut down.

$$T_{i,t}^{on} \geq MUT_i \tag{4.11}$$

Minimum Down-Time Constraints

A unit must be off for a certain number of hours before it can be brought online.

$$T_{i,t}^{off} \geq MDT_i \tag{4.12}$$

Unit initial status

The initial unit states at the start of the scheduling period must be taken into account.

4.5 Unit Scheduling for Emission Constrained Thermal Unit Commitment

Emission constrained thermal UCP can be dividing into two parts; first part is determining the on/off status of generating units in each time period of planning horizon and second is the unit scheduling problem [81].

4.5.1 Structure of individual for Emission Constrained Thermal UCP

Each population has two dimensions, one dimension for number of units (N) and second for time horizon (T). So, the on-off schedule of the units is stored as an integer-matrix U with dimension (N x T). A matrix representation of a population is shown as follow [81]:

$$U=\begin{bmatrix} u_1^1 & u_1^2 & \cdots & u_1^T \\ u_2^1 & u_2^2 & \dots & u_2^T \\ \vdots & \vdots & \vdots & \vdots \\ u_N^1 & u_N^2 & \dots & u_N^T \end{bmatrix} \tag{4.13}$$

Where u_i^t=unit on/off status of unit i at time t

4.5.2 Initialization of Unit Combination in population

A set of unit combination is created at random. For the complete L population, the candidate solution of each particle is randomly initialized. Unit combination has three dimensions because population dimension will be introducing (L). The on-off schedule of the units is stored as an integer-matrix U with dimension (L x N x T). A matrix representation of initialization of unit combination with population is shown as follow:

$$U=\begin{bmatrix} \begin{bmatrix} u(1,1,1) & u(1,1,2) & \dots & u(1,1,T) \\ u(1,2,1) & u(1,2,2) & \cdots & u(1,1,T) \\ \vdots & \vdots & \vdots & \vdots \\ u(1,N,1) & u(1,N,2) & \cdots & u(1,N,T) \end{bmatrix} \\ \begin{bmatrix} u(2,1,1) & u(2,1,2) & \dots & u(2,1,T) \\ u(2,2,1) & u(2,2,2) & \dots & u(2,2,T) \\ \vdots & \vdots & \vdots & \vdots \\ u(2,N,1) & u(2,N,2) & \dots & u(2,N,T) \end{bmatrix} \\ \vdots \\ \vdots \\ \begin{bmatrix} u(L,1,1) & u(L,1,2) & \dots & u(L,1,T) \\ u(L,2,1) & u(L,2,2) & \dots & u(L,2,T) \\ \vdots & \vdots & \vdots & \vdots \\ u(L,N,1) & u(L,N,2) & \dots & u(L,N,T) \end{bmatrix} \end{bmatrix} \tag{4.14}$$

Where u (j, i, t) =unit on/off status of i^{th} unit at time t for j^{th} population

L=population

N=number of generating units

T=time period for scheduling

4.5.3 Priority list for unit-scheduling

Priority list is created according to each unit parameters. Cost per produced unit, of a unit at its maximum output power usually is less than that at other output power levels. Priority list is based on fuel cost obtained from the average fuel cost of each unit operating at its maximum output power [81]. The average full-load cost α of a unit is defined as the cost per unit of power ($/MW) when the unit is at its full capacity . When the fuel cost of unit is given by Eq. (4.4), α can be expressed as

$$\alpha_i = \frac{F_i\left(P_{i,t}\right)}{P_i^{max}} = \frac{a_i}{P_i^{max}} + b_i + c_i \times P_i^{max} \tag{4.15}$$

The units are ranked by their α in ascending order. Thus, the priority list of units will be formulated based on the order of α_i, in which a unit with the lowest α_i, will have the highest priority to be dispatched.

4.5.4 Spinning reserve constraints

The obtained primary unit-scheduling may not satisfy the spinning reserve constraints (4.9). Therefore, the spinning reserve violations are repaired by heuristic search. The flowchart for repairing the spinning reserve violations in primary unit-scheduling is shown in Fig.4.1 [82]. The algorithm for repairing the spinning reserve violations in emission constrained thermal unit commitment problem is as follows [81]:

Step 1. Set j=1

Step 2. Set t=1

Step 3. For all uncommitted units at hour t, calculate the average full-load cost α_i using Eq. (4.15).Sort them in ascending order of α_i to obtain a unit scheduling list $S(\alpha_i)$.

Step 4. The amount of excessive spinning reserve at each hour is calculated by

$$Z_{j,t} = \sum_{i=1}^{N} U_{j,i,t} \times P_i^{max} - P_{d,t} - R_t \tag{4.16}$$

Step 5. If $Z_{j,t} \geq 0$**,**go to step 6

Step 6. Commit an uncommitted unit in $S(\alpha_i)$ with the lowest α_i,one unit at a time until the spinning reserve constraint is satisfied.

Step 7. If t<T, t=t+1 and return to step 3

Step 8. If j<L, j=j+1 and return to step 2.otherwise, stop.

4.5.5 Minimum up and down time constraints

Since the obtained unit schedule may not satisfy the minimum up/down constraints, a heuristic search algorithm is required to repair any violations of these constraints. The flowchart for repairing the minimum up time and down time constraints in primary unit-scheduling is shown in Fig.4.1 [82]. The continuously on/off times of the i^{th} unit up to hour t are calculated as follows [81]:

$$T_{j,i,t}^{on} = \left(1 + T_{j,i,t-1}^{on}\right) \times U_{j,i,t} \quad (4.17)$$

$$T_{j,i,t}^{off} = \left(1 + T_{j,i,t}^{off}\right) \times \left(1 - U_{j,i,t}\right) \quad (4.18)$$

Where $T_{j,i,t}^{on}$ =continuously on time for i^{th} unit upto time t

$T_{j,i,t}^{off}$ =continuously off time for i^{th} unit upto time t

The procedure to repair violations of the minimum up/down times constraints are as follows:

Step 1: Calculate the duration on and off times of all units for the whole schedule time horizon using Eq. (4.17) & (4.18).

Step 2: Set j=1

Step 3: Set t=1

Step 4: Set i=1

Step 5: If $U_{j,i,t} = 0$ and $U_{j,i,t-1} = 0$,then

5(a) If $T_{j,i,t-1}^{on} < MUT_i$,then $U_{j,i,t} = 1$

5(b) If (t+$MDT_i - 1 \leq T$) and ($T_{j,i,t+MDT_i-1}^{off} < MDT_i$), then $U_{j,i,t} = 1$

5(c) If (t+$MDT_i - 1 > T$) and $\sum_{m=t}^{T} U_{j,i,m} > 0$, then $U_{j,i,t} = 1$

Step 6: Update the duration on/off times for the i^{th} unit using Eq. (4.17) & (4.18).

Step 7: If $i < N$,$i = i + 1$ and return to step 5.

Step 8: If $t < T, t = t + 1$ and return to step 4.

Step 9: If $j < L, j = j + 1$ and return to step 3.Otherwise, stop.

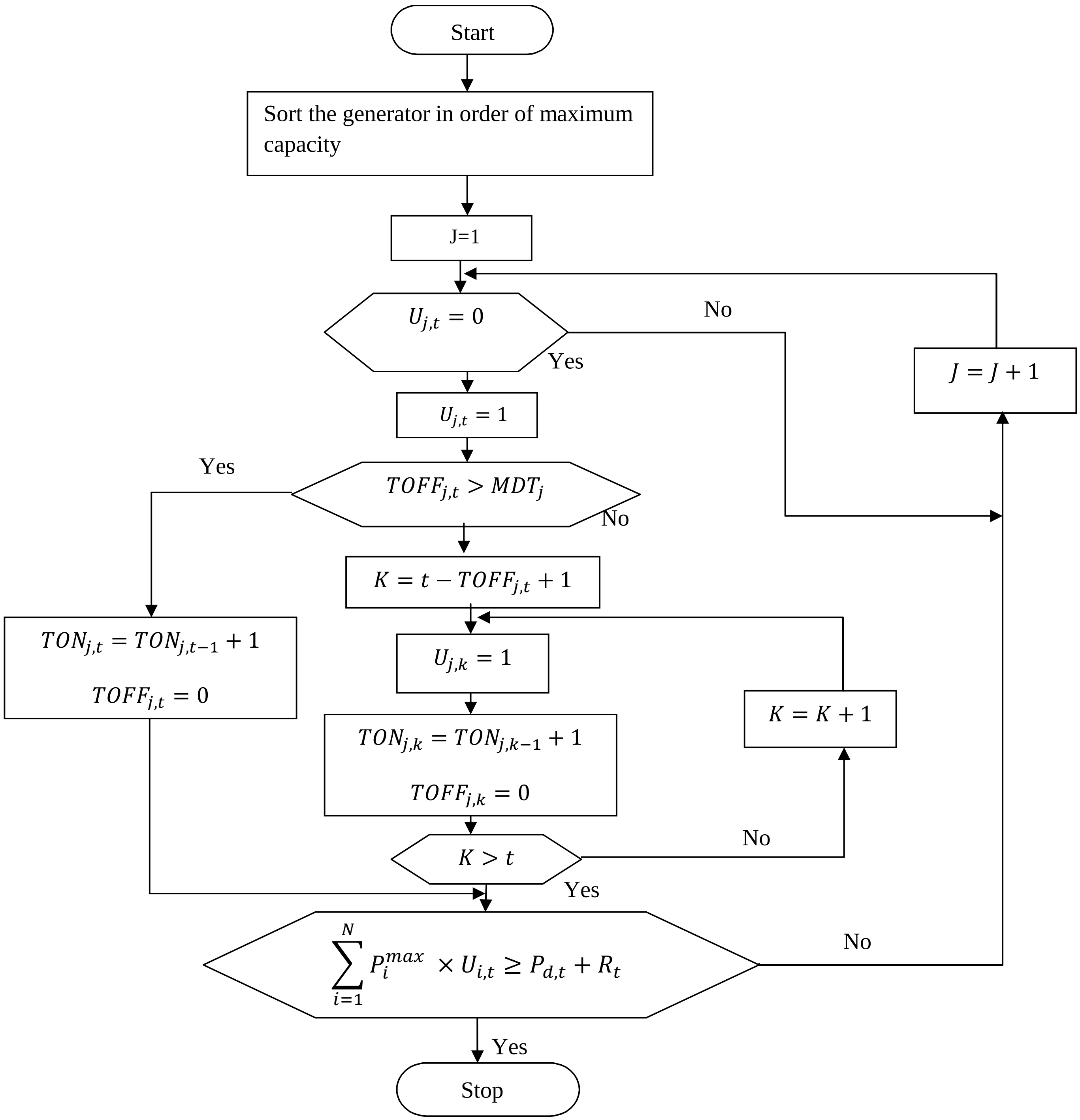

Fig.4.1 Flowchart of repair algorithm for handling spinning reserve constraint and minimum up time & minimum down time constraint

4.5.6 Decommitment of excess units

Repairing the minimum up and down time constraints can lead to excessive spinning reserves, which is not desirable due to the high operation cost. In a heuristic search algorithm based on a priority list to decommit the redundant units due to the minimum up and down time repairing, thereby reducing the operating cost. Starting from the committed units with the lowest priority list (the highest average operating cost), the algorithm determines units that can be decommitted without violating the minimum up and down time and spinning reserve constraints until no unit can be decommitted. So in this process, the spinning reserve and minimum up and down time constraints must be checked before decommitting a unit. The flowchart for repairing the de-commitment of excess unit for prevention of excess spinning reserve violations in primary unit-scheduling is shown in Fig.4.1 [82].

Procedure for decommitment of excessive units is as follows [81]:

Step 1: Set j=1

Step 2: Set t=1

Step 3: Calculate the average full-load cost α_i of each committed unit in hour t and sort the units in the descending order of α_i to obtain a list $S(\alpha_i)$. Let the first unit in $S(\alpha_i)$ be $CU_{j,t}$.

Step 4: The amount of excessive spinning reserve at hour *t* is calculated by

$$Z_{j,t} = \sum_{i=1}^{N} U_{j,i,t} \times P_i^{max} - P_d - R_t \tag{4.19}$$

Step 5: If $Z_{j,t}$ is less than the maximum generation power of $CU_{j,t}$,go to step 7.

Step 6: If decommitting $CU_{j,t}$ does not violate its minimum up/down time constraint, decommit $CU_{j,t}$ and update on/off status for all units.

Step 7: Delete $CU_{j,t}$ from $S(\alpha_i)$.

Step 8: If $S(\alpha_i)$ is not empty, let $CU_{j,t}$ be the first unit in $S(\alpha_i)$ and return to step 3.

Step 9: If $t < T, t = t + 1$ and return to step 3.

Step 10: If $j < L, j = j + 1$ and return to step 2. Otherwise, stop.

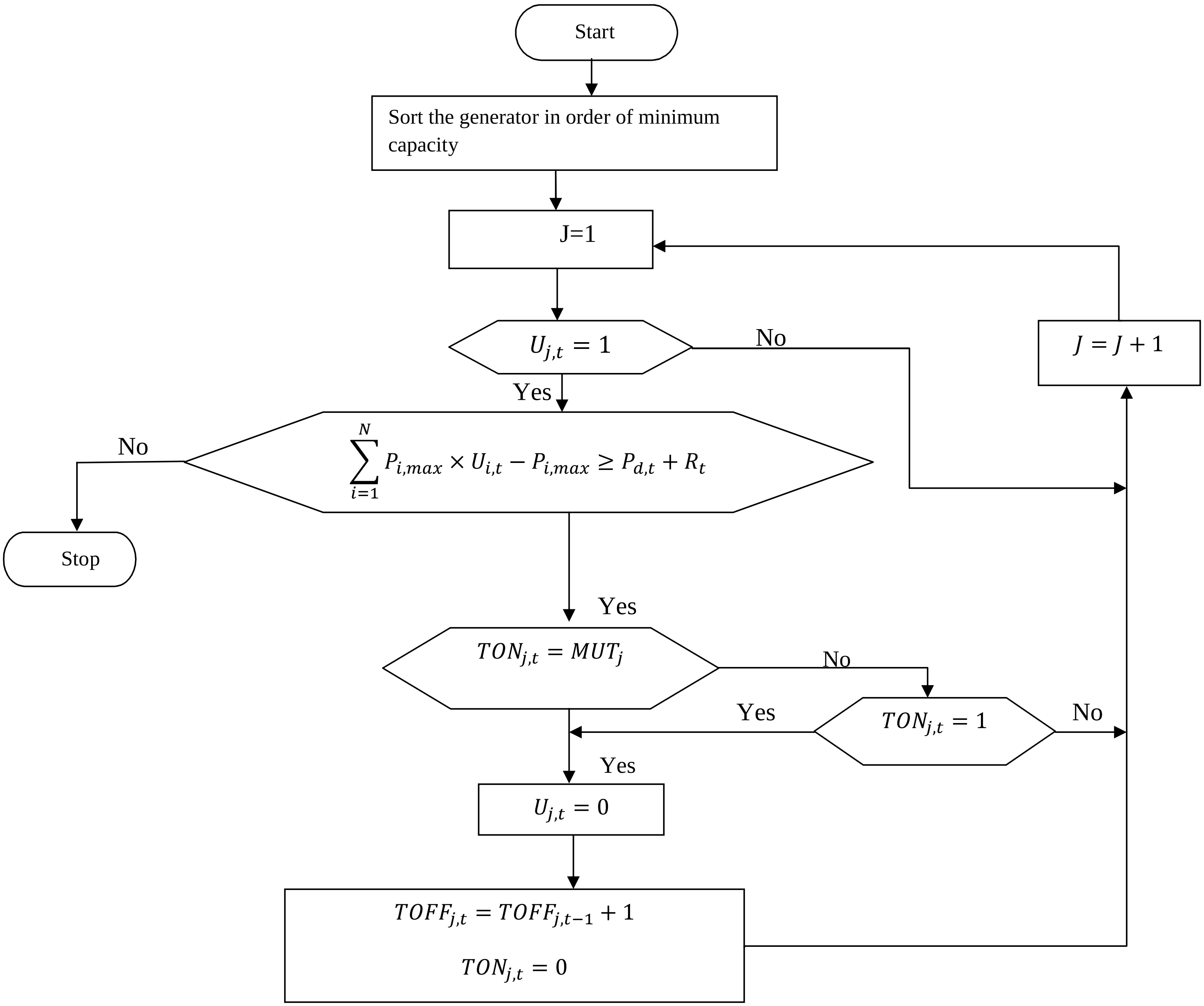

Fig.4.2 Flowchart of unit de-commitment for prevention of excess spinning reserve

4.6 Calculation of objective function

Objective function is minimizing the total operating cost, which include the production cost and starting cost. The procedure of calculate the objective function is as follow:

Step 1: Calculate the on and off time duration from Eq. (4.17) & (4.18).

Step 2: Set t=1

Step 3: Set i=1

Step 4: Calculate the error

$$error_{j,t} = \left(\sum_{i=1}^{N} P_{j,i,t} - P_{d,t}\right)^2 \ (j = 1,2, \dots, L; i = 1,2 \dots, N; t = 1,2, \dots, T) \quad (4.20)$$

$$error_j = \sum_{t=1}^{T} error_{j,t} \quad (4.21)$$

Step 5: Calculate the emission of the unit from Eq. (4.3).

Step 6: Calculate the penalty for additional emission purchase from Eq. (4.7).

Step 7: Calculate the objective function

$$F_j = \sum_{t=1}^{T}\sum_{i=1}^{N}[F_i(P_{j,i,t}) + E_i(P_{j,i,t})] \times U_{j,i,t} + \sum_{t=1}^{T}\sum_{i=1}^{N}[SC_{j,i,t} \times (1 - U_{j,i,t-1}) \times U_{j,i,t}] + M \times error_j + EMC \quad (4.22)$$

where M=A extreme penalty factor

Step 8: If $i < N, i = i + 1$ and return to step 4.

Step 9: If $t < T, t = t + 1$ and return to step 3.Otherwise, stop.

4.7 Algorithm for Emission Constrained Thermal Unit Commitment using DE

Step 1: Read data, viz. Cost coefficient (a_i, b_i, c_i), population size (L), boundary constraints of optimization variables (NG), mutation factor (FM), crossover rate (CR), and the stopping criterion of maximum number of iterations (IT_{max}), x_i^{min}, x_i^{max}, and unit commitment constant.

Step 2: Initialization unit combination as in Section (4.5.2).

Step 3: Calculate priority list of units according to each unit parameters as in Section (4.5.3).

Step 4: Modify unit's status of unit combination satisfying spinning reserve constraints as in Section (4.5.4).

Step 5: Repair unit's status of unit combination satisfying minimum up/down time violations as in Section (4.5.5).

Step 6: Decommit units of each hour to reduce excessive spinning reserve constraints and also repairing the minimum up/down times constraints as in Section (4.5.6).

Step 7: Randomly generate an initial population of each individuals using Eq. (3.1).

Step 8: Calculate the fitness of each individuals of initial population (target vector matrix) using Eq. (4.22), which is the total production cost of all units of the system.

Step9: Select the maximum fitness of the initial population, i.e., the minimum cost of production of the initial population and set as cost is F_j^{best} and $P_{j,i,t}^{best} = P_{j,i,t}$.

Step 10: Set iteration IT=1

Step 11: Perform mutation operation on initial population using Eq. (3.2).

Step 12: Calculate the fitness of each individuals of donor vector matrix using Eq. (4.22).

Step 13: Perform crossover operation on initial population using Eq. (3.3)

Step 14: Calculate the fitness of each individuals of trial vector matrix using Eq. (4.22).

Step 15: If fitness of the trial vector matrix is greater than or equal to the fitness of the target vector matrix, then the target vector matrix is replaced by the trial vector matrix using Eq. (3.4), otherwise, the target vector matrix remains the same.

Step 16: Calculate the new objective value by Eq. (4.22) and set as cost is F_j^{new}.

Step 17: If ($F_j^{new} < F_j^{best}$) THEN set ($F_j^{best} = F_j^{new}$) and ($P_{j,i,t}^{best} = P_{j,i,t}^{new}$)

Step 18: If the iteration is less than the maximum iteration $IT < IT_{max,} IT = IT + 1$ and return to step 10.

Step 19: Otherwise, STOP and F_j^{best} & $P_{j,i,t}^{best}$ give the optimum output.

CHAPTER 5

RESULT AND DISSCUSSION

5.1 Introduction

The previous chapters that have been studied provide the complete knowledge of Emission Constrained Thermal Unit Commitment and its formulation using DE. The algorithms of DE for solving the emission constrained thermal unit commitment problem are presented in chapter 4. In this section, two cases are studied to illustrate the effectiveness of the proposed method in terms of its solution quality. The spinning reserve is assumed to be 10% of the load demand.

Test system 1:

The test system consists of four generating units, 8-hr scheduling periods. Data on the generating units in which the fuel cost coefficients, emission coefficients, minimum up and down time and power limits are known. The specifications of the system for four generator test system are detailed in appendix -1.Test data is given in [83].

TABLE: 5.1 ECONOMIC SCHEDULING (Test System-1)

Case-1

Hour	Power Demand (MW)	Hourly Operating Cost ($)	Hourly Emission (kg)	Power Generations of Units (MW)			
				1	2	3	4
1	450	9609	724	298.6730	151.3270	0	0
2	530	11147	798	255	250	25	0
3	600	12520	911	298.0668	250	51.9331	0
4	540	11330	784	281.2868	214.9707	43.7425	0
5	400	8777	503	236.2193	116.0278	47.75286	0
6	280	6611	528	280	0	0	0
7	290	6862	441	250.3651	0	39.63491	0
8	500	10589	755	296.2451	178.6772	25.0777	0
Total		77445	5444				

TABLE: 5.2 EMISSION SCHEDULING (Test System-1)
Case -2

Hour	Power Demand (MW)	Hourly Operating Cost ($)	Hourly Emission (kg)	Power Generations of Units (MW)			
				1	2	3	4
1	450	9659	678	220.7588	229.2412	0	0
2	530	11340	681	211.8781	238.1219	80	0
3	600	12600	850	270.7553	250	79.2447	0
4	540	11500	702	237.5547	222.4453	80	0
5	400	8971	427	161.0181	158.9819	80	0
6	280	6612	526	280	0	0	0
7	290	7032	360	210.1156	0	79.8844	0
8	500	10785	615	202.7838	217.2162	80	0
Total		78499	4839				

TABLE: 5.3 EMISSION CONSTRAINED ECONOMIC SCHEDULING (Test System-1)
Case-3

Hour	Power Demand (MW)	Hourly Operating Cost ($)	Hourly Emission (kg)	Power Generations of Units (MW)			
				1	2	3	4
1	450	9613	708	283.8100	166.1900	0	0
2	530	11264	710	240.4825	226.3920	63.1255	0
3	600	12555	878	286.0543	248.8974	65.0483	0
4	540	11352	776	246.4586	250	43.5414	0
5	400	8908	451	194.5332	140.1472	65.3196	0
6	280	6611	528	280	0	0	0
7	290	6996	377	219.3275	0	70.6725	0
8	500	10703	655	232.8656	209.4332	57.7012	0
Total		78002	5083				

TABLE: 5.4 COMPARISONS OF RESULT FOR DIFFERENT CASES (Test System-1)

SI NO.	Test case	Emission output (kg)	Operating cost ($)
1	Case-1	5444	77445
2	Case-2	4839	78499
3	Case-3	5083	78002

Test system 2:

The test system consists of ten generating units, 24-hr scheduling periods. Data on the generating units in which the fuel cost coefficients, emission coefficients, minimum up and down time and power limits are known. The specifications of the system for ten generator test system are detailed in appendix -2.Test data is given in [83].

TABLE: 5.5 ECONOMIC SCHEDULING (Test System-2)

Case-1

Hour	Power Demand (MW)	Hourly Operating cost($)	Hourly Emission (kg)	Power Generations of Units(MW)									
				1	2	3	4	5	6	7	8	9	10
1	700	18498	8571	425.2161	0	126.0773	69.8412	0	0	78.8653	0	0	0
2	750	19606	9827	454.9628	0	96.1604	130	0	40.4962	28.3805	0	0	0
3	850	21901	7810	403.9187	0	108.3900	52.2244	162	20	35.0066	36.7903	0	31.6699
4	950	22784	8530	355.5790	263.4661	93.1597	109.6335	83.6740	44.4876	0	0	0	0
5	1000	23906	10403	365.9897	328.4280	86.8447	130	25	0	36.1561	0	0	27.5814
6	1100	26307	17409	455	455	0	0	130.3998	0	29.1102	0	30.4126	0
7	1150	26845	15791	451.0924	409.4207	110.9627	0	152.7863	0	25.7379	0	0	0
8	1200	27500	16804	434.0825	455	130	78.4165	61.2703	0	0	26.4382	0	14.7924
9	1300	30059	17783	455	455	130	120.2478	0	0	85	35.3167	0	19.4262
10	1400	31739	17784	455	455	80.3800	130	162	76.2777	41.3214	0	0	0
11	1450	33322	17903	455	455	130	126.8152	73.4179	57.1763	77.8312	29.1157	45.4978	0

12	1500	34146	17866	455	455	120.4775	113.6095	162	80	38.0472	55	20.7974	0
13	1400	31916	17895	455	455	130	120.3026	129.7625	0	70.7840	0	0	39.1230
14	1300	29997	17755	455	455	0	129.0234	154.0390	58.4168	0	37.9014	10.4521	0
15	1200	27908	16392	421.7800	455	112.6804	0	162	20.0234	28.5161	0	0	0
16	1050	25020	12576	452.9183	291.8904	112.0853	123.7515	0	0	57.9971	0	11.3574	0
17	1000	24528	14628	433.3683	401.4353	0	0	87.6742	21.0892	37.3198	0	0	19.1130
18	1100	25546	15245	451.2927	398.9016	80.1469	100.5968	29.5861	20.2367	0	19.2390	0	0
19	1200	27863	17088	450.0606	450.5665	113.1610	28.4827	59.3423	56.1285	30.6771	0	11.5811	0
20	1400	32066	17743	455	455	85.7486	130	162	0	57.2116	0	0	55
21	1300	29333	17730	455	455	130	78.8390	160.7841	0	0	20.3364	0	0
22	1100	25485	15842	414.6468	450.2978	34.9651	129.9623	0	0	70.1279	0	0	0
23	900	22603	13469	385.5405	417.5673	0	0	34.8932	0	25	10	26.9990	0
24	800	20372	7945	308.9598	303.5316	84.0571	0	74.5095	0	28.9418	0	0	0
Total		639250	350789										

TABLE: 5.6 EMISSION SCHEDULING (Test System-2)

Case -2

Hour	Power Demand (MW)	Hourly Operating cost($)	Hourly Emission (kg)	Power Generations of Units(MW)									
				1	2	3	4	5	6	7	8	9	10
1	700	19139	6869	364.3259	0	130	124.8344	0	0	80.8396	0	0	0
2	750	20263	6488	455	0	101.3720	44.7003	0	71.0386	77.0450	0	0	0
3	850	23351	3586	215.5026	0	130	124.2702	162	80	63.2996	26.7124	0	48.2151
4	950	23518	5850	258.5342	224.2689	130	130	127.1969	80	0	0	0	0
5	1000	25612	5391	189.8950	271.5027	123.5057	113.0966	162	0	85	0	0	55
6	1100	26431	13956	436.2800	443.2141	0	0	159.7604	0	26.1194	0	34.6261	0
7	1150	27445	13893	455	320.8695	130	0	162	0	81.8722	0	0	0

8	1200	27848	10866	419.4164	370.3120	101.6207	130	113.6510	0	0	55	0	10
9	1300	30231	17315	444.2401	455	130	113.8957	0	0	71.9145	46.9460	0	38.0036
10	1400	34225	17158	455	431.0363	130	130	162	46.9715	44.5887	0	0	0
11	1450	33867	14855	455	342.5544	123.6993	121.6945	162	62.3180	82.1667	45.2833	55	0
12	1500	34342	17427	440.7212	455	130	123.7327	129.9185	79.5644	80.2238	40.3393	20.4999	0
13	1400	32240	17197	450	432.2382	130	109.7748	132.7723	0	85	0	0	55
14	1300	30514	15632	405.9426	447.4520	0	122.8832	155.7541	70.9815	0	50.1816	46.8049	0
15	1200	28657	12719	379.2714	386.8478	129.1776	0	160.7175	73.5670	70.4185	0	0	0
16	1050	25648	9995	375.5313	290.0499	129.5026	129.4707	0	0	80.4201	0	45.0253	0
17	1000	25354	9235	448.9156	247.8717	0	0	129.8665	80	60.3112	0	0	33.0349
18	1100	26422	8402	258.6703	339.8646	125.7341	130	162	35.1830	0	48.5479	0	0
19	1200	29042	8297	319.9171	276.8289	130	127.0754	155.9877	79.8413	75.2621	0	35.0874	0
20	1400	34017	16850	455	426.2916	119.0189	130	146.8541	0	77.9931	0	0	44.4699
21	1300	29449	16906	455	432.0962	130	86.8899	162	0	0	33.9677	0	0
22	1100	26099	12643	403.5416	356.8370	124.6214	130	0	0	85	0	0	0
23	900	23968	7572	305.8752	288.6255	0	0	142.0733	0	62.1802	47.7166	53.5291	0
24	800	21182	4715	194.9847	319.9342	125.9818	0	95.4654	0	63.6339	0	0	0
Total		658864	273817										

TABLE: 5.7 EMISSION CONSTRAINED ECONOMIC SCHEDULING (Test System-2)
Case-3

Hour	Power Demand (MW)	Hourly Operating cost($)	Hourly Emission (kg)	Power Generations of Units(MW)									
				1	2	3	4	5	6	7	8	9	10
1	700	19069	7523	390.3496	0	130	99.4007	0	0	80.2496	0	0	0
2	750	20206	6567	351.4597	0	130	130	0	70.6376	67.9026	0	0	0
3	850	22197	7589	393.9283	0	53.5758	130	128.6517	33.8821	25	51.7814	0	33.1805
4	950	23176	6049	275.5547	227.8602	103.0470	122.6059	147.5930	73.3391	0	0	0	0

5	1000	24446	7120	273.5697	290.4309	58.3696	130	162	0	54.8322	0	0	30.7975
6	1100	26377	14105	455	455	0	0	117.4060	0	26.8781	0	45.1345	0
7	1150	26930	14423	450.3453	365.4932	124.9223	0	126.7109	0	82.5283	0	0	0
8	1200	27556	14143	455	345.2555	98.0942	130	150.5992	0	0	11.0208	0	10
9	1300	30111	17493	447.4507	455	120.4067	130	0	0	77.7000	55	0	14.4424
10	1400	31764	17459	455	444.0598	106.0835	130	153.1877	50.9124	60.6451	0	0	0
11	1450	33555	16614	455	424.8052	130	76.2020	141.4721	76.6909	85	36.3817	24.4191	0
12	1500	34286	17852	455	455	121.8973	114.6670	151.1270	59.4370	66.4223	55	21.4039	0
13	1400	32013	17221	438.3746	455	115.4367	122.2650	162	0	75.1464	0	0	31.7772
14	1300	30230	17669	455	455	0	124.7659	109.4181	80	0	30.7807	44.8848	0
15	1200	28192	14754	386.5786	442.3448	113.9730	0	157.3895	72.2715	27.4425	0	0	0
16	1050	25045	12071	424.1160	313.5936	128.2524	113.8969	0	0	49.6241	0	20.5170	0
17	1000	24838	11840	386.3128	361.0376	0	0	155.5425	51.0236	25	0	0	21.0834
18	1100	25732	11147	455	230.7577	61.3629	70.8380	162	80	0	39.5716	0	0
19	1200	28039	12254	281.8364	455	58.3042	119.8873	113.6751	56.6790	85	0	29.6178	0
20	1400	32199	17503	455	447.2653	130	95.9771	162	0	73.9823	0	0	35.5726
21	1300	29367	17654	455	455	93.9462	111.8048	158.6970	0	0	25.5116	0	0
22	1100	25516	15303	442.0853	404.7465	124.9693	97.6116	0	0	30.5874	0	0	0
23	900	22633	10301	318.5731	380.5639	0	0	54.9059	0	60.4252	55	30.5317	0
24	800	20660	7102	269.0132	295.0779	130	0	80.9088	0	25	0	0	0
Total		644137	278799										

TABLE: 5.8 COMPARISONS OF RESULT FOR DIFFERENT CASES (Test System-2)

SI NO.	Test case	Emission output (kg)	Operating cost ($)
1	Case-1	350789	639250
2	Case-2	273817	658864
3	Case-3	278799	644137

5.2 Parameter Setting

In the research work, Differential Evolution (DE) is used to solve the emission constrained thermal UCP .The success of DE is heavily dependent on setting of control parameters. It has three control parameters: (1) the population size NP (2) the mutation factor FM, which is a real-valued factor that controls the amplification of differential variation and (3) the crossover factor CR, which is also a real-valued factor that controls the crossover operation.

One of the main problems in evolution strategies of DE is to choose the control parameters such that it exhibits good behavior i.e. it does not prematurely converge to a point that is not globally optimal or stagnate and has an acceptable rate of convergence toward the global optimum. Premature convergence may occur under different situations: the population has converged to local optimum of the objective function, the population has lost its diversity and the search algorithm proceeds slowly or does not proceed at all.

TABLE 5.9 Parameter setting

NP	FM	CR	IT_{max}
50	0.75	0.90	1000

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion

In this dissertation, the emission constrained thermal unit commitment problem is solved using a robust DE algorithm. The maximum penalty factor method is used to incorporate the emission cost. Priority list is used to handle the spinning reserve constraints and a heuristic search algorithm is incorporated to handle minimum up/down time constraints. The emission constraints are taken into account by calculating the cost of purchasing additional emission allowances whenever the total emissions of the system exceed a predefined maximum limit.

The performance of the DE method was tested on a system of four and ten generating units. The results of economic scheduling, emission scheduling and emission constrained economic scheduling are compared. The results show that the price of emission allowances has a major effect on the final solution of the emission constrained thermal unit commitment problem.

6.2 Scope for Future Work

Scope of work after implementing emission constrained thermal unit commitment using DE is summarized as:

(1) The importance of emission control indicates the need for further work in this area by considering other emission parameters SO_X, NO_X along with CO_2.

(2) This emission constrained thermal unit commitment problem can be solved using shuffled frog leaping algorithm.

(3) This technique can be hybridized with particle swarm optimization (PSO) and ant colony search algorithm.

APPENDIX

APPENDIX 1:

TABLE A.1: Input data for four generating units and 8–hour scheduling

	Unit 1	Unit 2	Unit 3	Unit 4
P^{max}(MW)	300	250	80	60
P^{min}(MW)	75	60	25	20
a($/h)	684.74	585.62	213.00	252.00
b($/MW h)	16.83	16.95	20.74	23.60
c($/MW^2 h)	0.0021	0.0042	0.0018	0.0034
α($/h)	13.8593	13.8593	40.2699	40.2699
β($/MW h)	0.3267	0.3267	-0.54551	-0.54551
γ($/MW^2 h)	0.00419	0.00419	0.00683	0.00683
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

TABLE A.2: Load Demand for 8-Hour

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

APPENDIX 2:

TABLE A.3: Input data for ten generating units and 24–hour scheduling

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
P^{max}(MW)	455	455	130	130	162
P^{min}(MW)	150	150	20	20	25
a($/h)	1000	970	700	680	450
b($/MW h)	16.19	17.26	16.60	16.50	19.70
c($/MW^2 h)	0.00048	0.00031	0.002	0.00211	0.00398
α($/h)	360.0012	350.0056	330.0056	330.0056	13.8593
β($/MW h)	-3.9864	-3.9524	-3.9023	-3.9023	0.3277
γ($/MW^2 h)	0.04702	0.04652	0.04652	0.04652	0.00420
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

TABLE A.3: (Contd.)

	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
P^{max}(MW)	80	85	55	55	55
P^{min}(MW)	20	25	10	10	10
a($/h)	370	480	660	665	670
b($/MW h)	22.26	27.74	25.92	27.27	27.79
c($/MW^2 h)	0.00712	0.00079	0.00413	0.00222	0.00173
α($/h)	13.8593	40.2699	40.2699	42.8955	42.8955
β($/MW h)	0.3277	-0.5455	-0.5455	-0.5112	-0.5112
γ($/MW^2 h)	0.00420	0.00680	0.00680	0.00460	0.00460

min up time (h)	3	3	1	1	1
min down time(h)	3	3	1	1	1
Hot start cost ($)	170	260	30	30	30
Cold start cost($)	340	520	60	60	60
Cold start hrs(h)	2	2	0	0	0
Initial status(h)	-3	-3	-1	-1	-1

TABLE A.4: Load Demand for 24-Hour

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

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