Chapter 1

Introduction

1.1 General

Economic operation of a power system is one of the goals of power system planning activities. Economic criteria is applied in long term and short term planning as well as in real time operation planning. Real time operation is characterized by second to minute duration. In short term planning operation, the period may be 24 hours or a week and in long term planning, time horizon may be one year. Normally, in long term planning, the main criteria considered are seasonal variation of load, fuel availability, availability of water, maintainability or refueling of nuclear plants. In short planning for 24 hours or a week, the main criteria considered are cyclic variation of load, selection of generation units according to the load variation as well as allocation of generation on every unit.

Importance of economic operation was realized right from the beginning of era of commercial generation and distribution of electric power. In early days, the main source of power generation was coal. Coal costs usually used to depend on quality of coal and cost of transportation. Secondly, the major equipments in power station such as boiler, turbine and generator have varying operating characteristics resulting in variation of efficiencies of different units at a station. Moreover, since index of efficiency is related to economy, ordering of units in those days used to be done on the basis of relative efficiencies; that is, the most efficient unit was operated first, then as the load increased requiring more generation capacity, next unit from the merit order of efficiency was loaded. Later, when the equal incremental [6] cost criteria was introduced, it brought about a complete change in the philosophy of economic operation of the power system. Today, almost at all installations, equal incremental fuel cost remains the main criteria for estimation of generation allocation on every unit of the power plant. However, various mathematical methods have been developed for economic operation of the power system and these are gradient method, linear programming, quadratic programming, dynamic programming[8] and the latest expert system and artificial neural network [3, 31]. In addition to above techniques, different researchers adopted variety of qualitative criteria such as transmission losses, stochastic variation of demand, reliability and security [6,23,44]. Following the alround progress and variety of contributions made by researchers, presently, the economic operation embarrassed mainly the following procedures.

(i) Unit commitment

(ii) Generation allocation or dispatching

(iii) Maintaining voltage stability and /or system stability, and

(iv) Demand side load management

The quality of power system is characterized by continuos or uninterrupted power supply at rated frequency and voltage without violating environmental balance. Therefore, the terms - reliability, security, maintenance scheduling have been introduced and attempts are made to achieve the best quality of power generation, transmission and distribution. Of course, the fulfillment of all the above aspects have been possible due to alround developments of mathematical techniques, sophisticated control equipments, best quality materials, highly efficient boilers, turbine, generators and their auxiliaries and accessories.

At present, the sources of power generation are coal, nuclear, hydro, gas,oil and wind. However, right from the beginning, coal plays a prominent role and its share is as high as 70% to 75% in all power systems. Inspite of use of other sources of power generation, in India coal will continue to dominate the picture and hence power system planners will have to concentrate on optimum utilization of coal in power generation. Even though the share of other sources are small, they are considered important in power system planning. Particularly, the plants based on hydro, gas, and oil can be synchronised in short times and they are mostly used to share peak loads because of limited availability of gas oil and water. Therefore to utilize the scare resources efficiently and run such plants optimally in coordination with thermal plants, mathematical techniques have been developed and employed. Due to ever increasing power demand in developing countries like India, there is a continuous ongoing activity of enhancing capacity installation, mainly utilizing coal even though other sources like hydro and gas are also being explored. The modern trend is to install large size units of the order of $210MW, 500MW$ which require large quantity of coal. However, these coal based power plants release emission of pollutants in atmosphere. The emissions are oxides of Sulphur, Nitrogen and Carbon. Emission of these pollutants in large quantity is naturally very harmful to all sorts of life. Hence, attempts are made to minimize or control these emissions to acceptable safety level. There are mainly two ways of controlling these emissions; viz, (1) to install additional equipments for removal or reduction of pollutants and (2) to minimize emissions by adjusting generation of committed units or to prepare unit commitment schedule so as to minimize the emissions.

Availability of large quantity of gas in India, has enhanced the energy sources. However, these plants are operated as fuel constrained plants because of controlled supply of gas by supply agencies. Recently attempts have been made to generate electric power from wind, mini and micro hydro plants but their share is not yet appreciable. The aim of economic operation of power system is to generate power at minimum cost by preparing unit commitment schedule and maintenance schedule over a specified time interval subject to various constraints. The normal practice is to estimate unit commitment first and then from committed units dispatch program is run [7]. However, dispatch calculations are performed during unit commitment procedure to arrive at proper decision.

1.2 Definitions

Unit Commitment: Unit commitment involves determining startup and shutdown schedule for the generating units over a short period, that is, 24 hours or a week to meet load demand, at minimum cost. Unit commitment normally handles thermal units, hydro and fuel constrained units can also be included for overall efficacy.

The objective of minimum cost involves satisfying a set of operating constraints. The main constraints are:

(i) Minimum up-time and down-time constraint

(ii) Generation constraint

(iii) Reserve constraint

(iv) Emission level constraint

Generation Scheduling: The generation scheduling is the determination of generation level of each committed units at minimum cost subject to equality and unequality constraints. It is also termed as 'Economic Dispatch'.

Environmental Dispatch: Environmental or Emission dispatch is the determination of generation level of each unit to minimize emission level subject to usual constraints.

Mix-Generation System: Mix-generation system comprises more than one generation source, such as thermal, hydro, nuclear, gas, wind etc.

Environment and Economic Dispatch: Environment and economic dispatch is the determination of generation allocation at each plant subject to equality and unequality constraints as well as environmental or emission constraint at minimum cost.

1.3 State of Art

Abundant literature is available on unit commitment, hydrothermal dispatch, environmental dispatch and thermal dispatch. This section will deal mainly with unit commitment, hydrothermal, Mix generation and environmental dispatch. A detailed survey on dispatch is available [4, 11, 12]. However, the literature which is closely related to our research topic is surveyed here.

1.3.1 Generation Scheduling

Aim of generation scheduling is to allocate generation share among the units at a plant or to allocate generation among plants of a system at a minimum cost. Main techniques available for the same are Lagrange multiplier [6], Gradient technique of first and second order [8], Dynamic Programming, Linear Programming [8], etc. Among all these methods those involving Lagrange multiplier are widely used in utilities. A very simple method to calculate generation scheduling is presented by Shrikrishna and Ramaraj [13] in which generation on every unit is expressed in terms of reference unit (normally first from the list). However, their method is not applicable for a system consisting of more than three units. Moreover, it is iterative. The same method is modified by Indulkar [15] which is non-iterative and exact; however, again the same is not applicable for more than three units. But Indulkar [15] has developed an idea to represent total cost by an equivalent function. Shrikrishna and Ramaraj [14] further presented a graphical method for generation scheduling including transmission losses. Units in a plant or number of plants in a system are not limited to three. A method irrespective of number of units is presented by P.S. Kanan [16]. The method is based on Lagrangian multiplier and modifies the basic co-ordination method. The approach is direct and can include transmission losses as well as bounds on units very easily. The technique of Generation allocation in terms of a reference unit is further developed by Ramaraj [17] which can be applied to any number of units of a system. However, basically formulation depends on Lagrangian multiplier. Methods available for generation allocation including transmission losses are iterative to find λ. Ramraj [18] has developed technique which eliminates the conventional iterative procedure of estimating λ. This 'no - λ' iteration technique involves transforming the co-ordination equation in 'N' optimized plant output equations. Optimum generation of the individual plants can be calculated by substituting merely demand in these equations. However, the optimized plant equation is a third order polynomial. The positive root determination of such equation takes [19] the same time as that of iterative method. A highly efficient method capable of solving large size problem in short time with online application is presented by C. Palanichami [19], The resulting equation is simple and gives the plant generation directly. The method takes into account the changes in network topology and system loads. The B-coefficients are used for the determination of line losses and incremental transmission losses.

All the above methods basically depend on Lagrangian multiplier. Dynamic Programming (DP) is basically a different method. Zi-Xiong [22] has reported a method which uses DP technique and zoom feature is applied to estimate economic dispatch including transmission losses. In most of the methods, generation allocation is estimated for units at a plant or for plants of a system, but no attention is given to include all units of the system in a generalized form. To estimate generation at a plant, equivalent cost functions are assigned and very few have reported the methods to estimate the equivalent cost function of a plant comprising a set of units. C.E. Lin and Viviani have used [25] equivalent cost function for economic dispatch having piecewise quadratic cost functions. Further, Wood and Woolenberg [8] has given an approximate method to calculate equivalent cost function. P.S. Kanan [27] have attempted to find composite cost function. Another attempt is is made by Narendiran [28] to evolve equivalent cost function for a set of third order polynomials. These expressions are derived by using the direct equation for optimum generation scheduling and total plant cost along with least square fitting technique with no approximations. An accurate method for equivalent cost function is presented by N. Ramaraj [30]. The method can be usefully extended directly to evolve the equivalent cost functions of plants in any power system having many areas. The procedure is based on incremental cost curves of the units. Kanan and Nityanand [29] have presented one more method to estimate equivalent cost function which is a second order polynomial. The method also takes into account limits of generation units. The equivalent cost function is basically derived from coordination equation. The equivalent cost functions are required to calculate area generation or the same is required for hydrothermal dispatch and in fuel constrained generation scheduling. In his attempt to present short term economic dispatch for fuel constrained plant, N. Ramaraj [30] have developed another equivalent cost function which is formed using incremental cost curve of the individual units.

1.4 Environmental Dispatch

Environmental dispatch normally takes into account generating unit incremental impact characteristics which include the effects of power system auxiliaries, in addition to above, transmission losses and effects of station apparatus which contribute to or reduce environmental impact. The complexity of environmental dispatch [38] problems stem from the fact that many variable factors determine the way power plants contribute to environment pollution. Some important factors are the type and grade of fuel applied, general topology of geographical area, proximity of other industries and prevailing climatic condition. Gent and Lamount [39] were the first to publish Minimum Environment Dispatch (MED). The method is analogous to economic dispatch, that is instead of using input BThU/MW output curve, they modelled the units representation by ton/hour versus MW output. Even though the attempt was simple, it was encouraging to researchers in this area. In emission dispatch various pollutants, like Nitrogen oxides, sulphur oxides and particulate are considered seperately. Depending upon the type of pollutants and available data, the curves are expressed as linear, second order polynomial and combination of the two or exponential [38]. Gent [39] in his attempt to minimize emission, came to the conclusion that it is possible to minimize emission but at the same time the cost of generation increases. However, the loss of economy due to minimization of emission is a valuable investment in clean air. A detailed review of economic and environmental dispatch is presented by Radivof Petrovic and B. Kralj [38] They have provided review of attempts made for environment protection and the strategies adopted. Delson [40] introduced the concept of controlled emission dispatch. He assumed cost of minimization as the main criteria and imposed constraint of emissions for NOx and SOx. J.B. Cadogan [41] has presented a dynamic emission management system for on-line control of Sulphur Oxide emission from fossil-fired generating plants. The basic concept of the system is that no single operational strategy is optimum for the vast combination of operating conditions and meteorology typically encountered on a power system,and as such a multiple strategy approach is desirable. The dynamic emission management system involves six strategies for economic and emission control of generation and allows the system operator/dispatcher to select the strategy most appropriate to the system at a particular time. In many installations, there are two types of fuels. A high-priced fuel containing low sulphur and low-priced fuel containing high sulphur. Hence, in addition to minimize the cost, sulphur content in fuel can be controlled by controling output of generating units, so as to satisfy total SOx emission constraint. The problem of this sort is solved by Akihiro Tsuji [42]. This paper describes optimization method to determine economic load dispatch as well as the optimum mix-ratio of high and low sulphur fuels (fuel mix), with the constraint on total sulphur dioxide emission per hour. The coupling method has been proposed for this purpose and the decoupling is considered for application to on-line control. The coupling method is based on the criteria due to Kuhn-Tucker on the assumption that sulphur content in fuels is controllable as continuously as the power output. A solution to the multi-objective problem such as Economic Emission Load Dispatch (EELD) which accounts for minimization of both cost and emission, is provided by J. Nanda, D.P. Kothari and K.S. Lingamurti [43]. They used Goal Programming (GP) technique for the solution of EELD. Goal Programming is an extension of Linear Programing (LP) or Non-Linear Programming (NLP). Though formulation of GP is similar to the formulation of LP/NLP, it differs in the approach to the solution. GP is capable of handling decision problems with single or multiple goals of conflicting nature. The method of GP consists of formulation of an objective function in which the optimization comes as close as possible to the specified goals. In their work, EELD problem is solved through linear and non-linear GP algorithms. The problem is defined in usual form assuming quadratic cost function and quadratic emission function. Emission function is assumed to include SOx, NOx, thermal emission and particulate. The presentation is claimed to be quite attractive for practical applications. A novel and efficient algorithm to obtain the optimal power flow in power system operation and planning is proposed by R.Yokoyama [44]. The proposed algorithm has made it possible to treat the optimal dispatch problem with multiple performance indices and to grasp trade-off relations between selected indices. The effect of uncertain factors pertaining to power system are also taken into account. They have defined multiple objectives such as economy, reliability and minimum influence on environment. These objectives are contradictory to each other and are in trade-off relations. In their method, optimal load flow problem is first formulated as a multi-objective optimization problem then ϵ constrained technique is used to obtain a set of non inferiority solutions and further, the idea of preference index is introduced to decide the optimum solution. In their work, they used security as preference index. Fuel switching [42], in which low sulphur fuels replace high sulphur fuels, has been identified as a cost effective means of decreasing SOx emission. However, this may lead to losses of coal field jobs. A model is prepared for evaluating the cost and employment impacts of effluent dispatching and fuel switching as a means for reducing emission from power plants [45] the algorithm performs fuel switching and generates trade-off among multiple objectives and incorporates modern probabilities production costing methods. The method is suitable for planners and policy analysts to understand trade-off between costs, emission and if desired, employment in fuel producing regions. However, the model is unable to consider the benefits of capital investment for lowering emission. As discussed earlier [43] in goal programming technique different criterias are defined but the inter-relation between them are not taken into account. A trade-off relationship is being considered by Karamshahi et al [46]. They have presented the method for optimization and coordination of total generation cost and total NOx emission together with their trade-off relationship. The procedure formulates dispatch problem as multiple objective optimization problem with non-commensurate objectives. Each objective is optimized by powel's method in the light of individual performance index. Goal Programming is quantitatively performed to grasp trade-off relation among the conflicting objectives; and then method of sensitivity analysis is applied to evaluate the environmental marginal cost which indicates the increased portion of the cost of system operation while impact on environment is improved. The problem of emission reduction is difficult to be solved due to operation of old thermal plants (which must continue to be operated to meet ever increasing demand) and shortage in the availability of less polluting fuels. Therefore attempts are directed only to reduce the impact on environment. G.P. Graneli et al [47] have proposed dynamic dispatch procedure which is capable of taking into account the integral nature of emission constraint. The mixing of fuels with different pollution rates and the management of multifuel plants are taken into account with the purpose of obtaining a cost-effective operation for thermal plants in compliance with emission limitations. A suitably modified version of the Han-Power algorithm is employed to find a solution for the resulting large scale Non-Linear Programming problem. Under US clean air act 1990, many utilities will be considering a wide range options for controlling SOx and NOx emissions. Among these strategies are retrofits of emission control equipments, boiler modification , fuel switching, coal cleaning, emission dispatching, trading of emission allowance and energy conservation. Most of these options would change the cost and emission characteristics of generating units. To coverup these aspects, W. Huang et al [48] have presented a method for estimating the marginal system costs and emission caused by changes in the fixed cost, variable cost, emission and capability of units. The method is based on second order Taylor series expansion of unit output as calculated by probabilities production simulation. A review of clean air act of 1990 and impact of the enactment on the industrial practices related to economic dispatch problem is presented by A.A. Ez-keib [49]. Further, the problem is investigated in view of new SOx and underutilization constraints. US clean air act of 1990 is to be implemented in two phases. In phase one, the emissions for a utility will have an annual cap on affected units only. In phase two, starting from January 2000, all fossil fired plants with greater than 25 MW will be capped. Naturally, due to these strict constraints, power system planning and operation strategies will have to be modified, for which some of the viable options are:

(i) To use low sulphur coal or optimum fuel mix ratio of high and low sulphur fuels.

(ii) Use of natural gas.

(iii) Use of scrubbers; the option to reduce approximately 90% of SOx emission for all power levels.

(iv) Load shift from one unit with high emission rate to that with lower one.

(v) Purchase of allowance.

Towards this end, two formulations of the economic dispatch are presented. One formulation considers SOx and under utilization requirements as constraints to be satisfied at each dispatch interval and is based on LR method. The other formulation uses the compensating generation provision to comply with the burn requirements. Both problems are simple and use a conventional economic dispatch with minor modifications to include a fuel cost adder. A new hierarchical power dispatch is presented by Yong- Lin Hu [50] which uses a combination of the off-line and on-line subsystems to minimize cost and emission. A hierarchical structure is introduced in the off-line subsystem which enables the subsystem to generate a course-to-fine guide line for balancing the cost and emission. The on-line dispatch is computed according to the guide line provided by off-line system. The dispatch is fed back to update the off-line computation layer by layer. In this way, the off-line guideline can always be adapted to the current situation, and overall dispatch tends to be optimal for a whole year period. Talaq J.H. [51] has provided a summary of environmental/economic dispatch algorithms. A conceptually simple and easy for programming, the approach is supplemented by C.Palanichami et al [52]. He has developed algorithms for minimum cost, minimum NOx emission, combined economic and emission and minimum cost with controlled emission dispatch. A price penalty factor h is defined which blends the emission costs with normal fuel costs. The optimization is based on the work [18] which circumvents the iterative approach. In his test objective to obtain appropriate value of h, large off-line calculations are required but on-line time and steps are reduced. Another approach to evolve minimum emission dispatch is presented by Ramaraj [53]. This paper presents a direct method to minimize the pollution caused by thermal plants. Peculiarity of his work is the development of quadratic cost function to compute fly-ash release as per loading of generators. And combining this function with cost function, he has used direct method to reduce the cost of generation.

1.5 Mix Generation Scheduling

Hydro and gas systems play very important role in thermal coordination. Major cost of generation in the thermal system is due to coal and, if hydro subsystems is coordinated with practically no fuel cost, will result in saving in cost of power generation. Similarly, gas availability has enhanced power generation scenario. Though there occurs production cost due to gas unlike that in hydro system, gas is supplied in fixed volume in a stipulated period and hence its cost is constant. Numerous methods have been developed for the solution of hydro-thermal dispatch. Techniques used for the same are applied as per operational features of the hydro-thermal system. Main features of hydro system are fixed head, varying head and cascaded hydro plants. Some plants are mainly aimed at power generation only. Whereas some are multipurpose or peaking plants or pumped storage. Normally, variables taken into account are discharge, inflow, spillage and head. Most of the problems solved, use deterministic model of hydro system. Gradient method is [130] widely used for deterministic model. Chandllar et al [32] was probably the first to solve hydro thermal dispatch using Lagrangian multiplier. Dahlin [32] et al used Pontryagin maximum principle. The methodology is derived for power system with hydro plants having fixed head, varying head and hydraulic coupling. A method of separable programming technique is attempted by Saha et al [132]. Dynamic programming method is also applied by many researchers [8]. Singh and Agrawal [35] used DP for hydro thermal scheduling excluding transmission losses. L.P.Singh [35] used DP with fixed head in which transmission losses are included. Methods applying DP use definite step size for calculating generation allocation on thermal and hydro units. For units having fixed head, M.E. El-Hawray and J. K. Lagrangian used powell's hybrid method. The hybrid method avoids possible causes for divergence encounterd with application of Newton Raphson method [33]. Zaghlool M.F. and Truff F.C. [34] proposed a method using LU factorization method of the matrix in Newton's method formulation. Abdul H.A. Rashid & Khalid M. Nor have [36] presented a method which corrects Zaghlool method. The coordination equations are linearized so that the Lagrangian of water availability constraint is determined separately from the unit generation and unit outputs are computed easily once the water constraint Lagrangian multiplier is determined. In Unit commitment and dispatch thermal unit and fuel constrained units are coordinated by Goran [37]. He has described in his paper an approach for solving seasonal operation planning problem of hydro-thermal system wherein part of the thermal capacity consists of energy constrained natural gas units.

1.6 Unit Commitment

The main techniques employed for unit commitment (UC) are, Exhaustive Enumeration, Priority Ordering List, Dynamic Programming, Integer and Mixed Integer Programming, Branch and Bound, Linear Programming, Dynamic and Linear Programming, Separable programming, Network Flow, Lagrangian Relaxation, Expert system, Artificial Neural Network, Risk Analysis, and Simulated Annealing [127]

1.6.1 Exhaustive Enumeration

Enumeration process involves checking of all possibilities of states. A state that yields the optimum return is chosen as the acceptable state. Hence, in exhaustive enumeration process which is applied for unit commitment involves enumeration of all possible combinations of generating units. On completion of the process, the combination that provides least cost of generation is selected as optimal combination. K. Hara [60] was the first to publish unit commitment procedure based on enumeration. Their paper describes a method of scheduling thermal units. A cost function is defined which considers not only the operation cost of generating units but also cost of system reliability. The criteria for economic operation is defined to minimize the expected value of the function and on the basis of this criteria an equation which gives the optimum number of operating units as well as units for overhaul can be obtained. R.H. Kerr [61] has defined start-up cost and cooling rate. The no load cost and loading costs reflect fuel expenditure to run the units once started and placed on line. To obtain minimum cost of operation for certain combination of units, the startup cost criteria is applied. Their program determines whether advancing or delaying the starting or stopping timing of the unit in the trial schedule, would result in a system fuel cost reduction. One of the key features of their program is flexibility which can be extended for system planning. Along with the maintenance cost and startup cost criteria for unit commitments, numerous physical constraints are required to be met. Some of the constraints are identified in their paper, ' Large Scale Hydro-Thermal Unit Commitment method and result' by H.H. Happ [62]. They attempted the problem of predominantly comprising of thermal units and few hydro units. The methodology is in two steps. In first step, called suboptimizer, feasible schedule is obtained which is closed to the optimal. And in a second step called optimizer, the schedule is optimized.

1.6.2 Priority List

This method arranges the generating units in an order. The predetermined order is then used to commit the units such that the system load is satisfied. The ordering of units is based on specific guidelines. R.R. Shuolts [63] have presented criteria for preparing priority list. The technique takes into account the relative operating cost at the maximum efficiency. The operating cost depends on unit start-up cost, minimum run time and fuel cost. Based on this priority list, an attempt is made for single area and multiple area UC with import and export limits. Further, technique is presented to compute equivalent incremental fuel cost of a system which may be applied to single area or multiple area UC. Their program can be used for daily, monthly and annual operation planning. Further, the procedure is presented for allocating saving among the participating companies forming a pool on an equitable basis. Approach to the unit commitment by priority ordering based on, ' Average Full Load Cost' (AFLC) [64] is attempted by Lee. Even though priority ordering method is fast but Lee's experience [65] reveals that it does not provide optimal solution. Moreover, AFLC does not provide sufficient information for determining optimal or near-optimal commitment order. This is due to the fact that the AFLC reflects operational economics when unit is efficiently utilized, and assumption of efficient utilization is not justified for the last few units committed. In view of this difficulty another attempt by Lee [65] is presented. He determined priority ordering by introducing index called 'Commitment Utilization Factor' (CUF) in conjunction with AFLC. In this new approach, index reflects units' utilization along with its spinning capacity. It is quantitative measure on how efficiently the unit is utilized if it is committed under current load condition. Extension to this work is multiarea unit commitment [66]. In this approach, CUF is modified in view of impact of transmission interconnection constraint in multiarea. The method is claimed to be easy to implement, and efficient.

1.6.3 Dynamic Programming

Among all methods proposed for UC, Dynamic Programming (DP) is widely used. DP searches the solution space that consists of units status for an optimal solution. The search is made both in forward and backward direction. The method is a multistage and multistate decision process. The stage refers to the hour for which a strategy is decided. Combinations of units within a time period are known as states. L.G.Lowery [67] was the first to explore the feasibility of application of DP to UC. He has explained the basic recursive formulation and used for preparing UC table which provides information of units' status at every hour as per load variation for 24 hours. Guy J.D.[68] has reported unit commitment based on security criteria. He developed constrained search technique to determine which unit to shutdown or startup in future hours to minimize fuel cost. The methodology takes into account probability of available generating capacity at desired hour. For every combination of units, a risk factor is calculated and compared with threshold risk as an assurance of generating capacity of units. Preparation of UC table based on priority ordering is attempted by A.K. Ayoub et al [69]. They used the technique formulated by Lowery and formed the priority ordering. The priority order provides order of combination along with the range of operation. Based on this ordering, UC is finalized in three steps. In first step UC table is formed based on demand at every hour; and in subsequent steps, the table is corrected due to security and startup criteria. Pang C.K. et al [70] have presented dynamic programming sequential combination method (DPSC) for unit commitment in which available units are committed sequentially according to priority order. The method is computationally fast, however, its solution quality depends fully on priority commitment order. DPSC solution is often hampered by inappropriate commitment of last few units. To overcome this problem, DP-STC is presented by Pang C.K. et al [71]. This method employs an enumeration window which covers a set of available units whose commitment may violate the assumed priority commitment order. As the size of enumeration window increases, the solution quality gradually stabilizes but computational time grows exponentially. While taking decision, economic dispatch is performed to obtain minimum cost of operation for particular combination. Chen et al [72] have attempted the problem of UC integrated with dispatch. They used truncated DP with simplified dispatch. They claim that the method provides better solution in less time. For large number of generating units, many a times, it becomes difficult to solve the UC problem by DP due to rapid increase in computer resources. However, decomposition may offer possibility to reduce computer resources. In their paper, P.P.J. Van Den Bosch [73] have attempted the problem by decomposition and dynamic programming. The problem is decomposed into many subproblems. Each subproblem is solved by DP and a coordinator converges the solution of the subproblems to the final solution of the original problem. Another approach to the problem of large size system is attempted by [75]. Their approach features the classification of generating units into related groups so as to minimize the number of unit combination which are tested without precluding the optimal path. They have defined basis of grouping of units, and within the group a priority is fixed. The advantage of such class designation is that the units can be sequentially committed within each class without risk of omitting the optimal configuration. Attempt by Nieva R.A. [74] is combination of DP and Lagrangian technique. DP is applied in successive approximations, then reduced search range is determined for each successive iteration by means of Lagrange technique. DP technique is further applied to multiarea by Z. Ouyang et al [76] The goal in their work is to develop a multi area generation scheduling scheme that can provide proper UC in each area and effectively preserve the tie line constraints. Unit commitments are initially performed by DP followed by a series of heuristic optimization adjustments, where deficiency and surplus in the committed capacity are executed. The special feature of the work is that the rule based heuristic are generalized by studding the system behaviour and human expertize regarding the optimal system operation. A global optimization method is presented by K.D.Le et al [79]. The methodology is particularly developed for South Carolina Electric and Gas Company which consists of thermal, hydro, pump storage and gas based power stations. In deriving the optimal unit commitment schedule, the program analyses all system resources and uses dynamic programming search to systematically evaluate alternative generation schedules and based on this evaluation selects a strategy which minimizes sum of system startup, fuel, operation & maintenance and purchase costs. In certain systems, certain units are jointly owned. Idea of joint owner is due to economics of larger scale units and avoidance of over unit commitment in generating capacity. In his paper, Kusiç G.L et al [80] presents an approach to problem of dispatch and UC of wholly owned and commonly owned units. Operating strategies are described and modification to conventional dispatch and UC program are examined. DP is used as the basic technique to determine the optimum schedule for startup and shutdown of available units in addition to unit base generation and production costs. Most of the available methods [83] employ the spinning reserve constraint to model the reliability requirement. In this regard the total available generating capacity provided by the committed units should exceed the load by spinning reserve of the system. However, spinning reserve constraint does not reflect the outage rates of the generating units or the uncertainty of the forecasted load may not ensure a reliable schedule of the generating capacity. The available probability approaches to UC have mainly considered load uncertainty but neglected the outages of generating units in problem formulation. S.K. Tong et al [82] has presented a study based on the formulation which employs the unit commitment risk as a reliability constraint. The approach provides a rational modelling of the problem by considering the outages of the thermal units and the uncertainty of the demand. The thermal UC is optimized by DP. The calculation of the expected cost of the thermal generation and the evaluation of commitment risk are performed by the segmentation method. For hydro-thermal coordination, an expected incremental cost grid of thermal generation is constructed for different levels of hydro generating capacity by introducing a new algorithm which supplements the segmentation method with an efficient shifting technique. Gradient technique is then applied to use this grid in the optimal dispatch of hydro units. Many a times, scheduling of generators as per UC do not provide dynamic security of the system due to heavy power flow in inter area lines. Hence, it is essential to take into account dynamic stability limit in the UC program. However, the dynamic stability limit is a complex function of systems which is not available before generation schedule is determined by UC. Hence, naturally the procedure to include dynamic stability should be iterative. Yuan-Yih Hsu et al [83] has attempted this problem for multiarea system. A modified DPTC method is presented by Z. Ouyang et al [77] which is entitled as variable truncated DP (DP-VW). The method adjusts the window size according to the incremental load demand in adjacent hours and controls the program execution to fine tune the optimization interactively. Fuzzy Dynamic Programming application to UC is attempted by Chung-Ching Su [78]. The feature of this approach is that the errors in the forecast can be taken into account by fuzzy set notations. To reach an optimal commitment schedule under fuzzy environment, security constraint, generation cost and load demand are all expressed in fuzzy set notation and then fuzzy DP is applied to yield the desired commitment schedule.

1.6.4 Linear Programming

Linear programming (LP) involves optimization over both a linear objective function and linear constraint. In LP, it is possible to develop an algorithm that will predict exactly how changes in decision variables affect constraints and program objectives. The LP, which is used for UC and Economic Dispatch, allows system restrictions which can be formulated as linear combination of generator MW outputs to be accommodated. These include upper limit on MW transfer between areas and lower limits on time limited reserve. The LP is used for UC using priority list. M. Pickutowski et al [91] has used the LP to dispatch units at each time interval to minimize over daily or weekly load cycle. The method is based on revised simplex method. In the proposed methodology generator configuration, flow constraints and reserve are modelled, with capability for individual restrictions on any unit. E. Khodaverdian et al [92] have developed for thermal UC of large scale by using hybrid form of the Discrete Decision Linear programming (DDLP) and heuristic technique to obtain suboptimal but fully feasible schedules.

1.6.4.1 Dynamic and Linear Programming

In this, UC problem is solved using a regular DP or DP with successive approximation of the solution space. The LP solves the economic dispatch within UC for the calculation of production cost or optimal allocation of fuel. James G. Waight et al [93] has developed method that combine DP and LP such that the real operation constraints of reserve margin and ramp-rates are optimally met by the resulting generation schedule. In a first step, DP is used to obtain UC. In a second step, the problem is viewed as the optimal dispatch for a given set of units subject to reserve margin and other constraints. This constrained dispatch is obtained using LP with Dantzig-wolfe decomposition. Scheduling of generation and allocation of fuel using DP and LP is presented by H.P. Van Meeteron [94] to solve UC and fossil fuel allocation. In his methodology developed, with fuel dependent input-output curves (multifuel units are allowed to burn a variable mixture of different fuel types) he has chosen iterative decoupled approach based on both UC module and fuel allocation module. For a given UC, fuel allocation module allocates the available fuel to the units in an optimal manner. On the other hand, UC schedules the unit for the given allocation. Fuel allocation problem is formulated by using linear or piecewise linear models for both fuel supply and generating units.

1.6.5 Integer Programming

In an optimization problem when all variables are constrained to take only integer values, it is called integer programming problem. When some variables only are restricted to take integer values, the optimization problem is called as mixed integer programming problem [58]. A decomposable mixed integer programming model for simultaneous economic consideration of UC and short term dispatch of thermal power system is presented by J.A.

Muckstadt et al [84]. Another approach using (IP) is presented by A Turgeon [86]. In his paper, the method is formulated as mixed integer nonlinear programming. Following Bender's approach, the problem is partitioned into a nonlinear and pure integer nonlinear programming problem. The UC problem is solved by variational method and branch and bound algorithm.

The above methods are used relatively for small systems. John Shaw et al [87] attempted to solve large hydrothermal [87] unit commitment and hydrothermal dispatch problem. They used a dual programming approach to solve optimal control problem for each thermal and hydro unit. A realistic model is developed, for short term operation planning of large scale hydrothermal power system with high share of hydro, by H.Habibollahadeh et al [88]. He has employed Bender's method to decompose the problem with respect to integer and continuous variables. The master problem of this method contains only integer variables and considers UC of thermal plants.

1.6.6 Branch and Bound

Branch and Bound approach determines a lower bound to the optimal solution and then finds near-optimal feasible commitment schedules. The branch and bound tree is searched for the best solution [127] In branch and bound search is carried out for the optimal solution through an enumeration process that can be represented by a decision tree. At each node of the decision tree, a subset of the integer variables is fixed.. Each of the remaining free integer variable is allowed to vary continuously between 0 and 1, and is given a gradient cost. Each problem thus created is then solved and the solution is termed as low bound solution. Each low bound solution is checked against the constraints of the original problem. If it is feasible and the cost is less than the current upper bound, it is retained as a candidate and its cost is taken as new upper bound; otherwise, the same is discarded. When all nodes have been processed search is completed and incumbent solution is optimal. The work in this direction using a realistic and comprehensive model taking into account nonlinear and/or linear fuel cost functions, loading rates as a nonlinear function of shutdown time, is reported in [88]. The solution is based on branch and bound capacitated transshipment approach that allows the exploitation of the ever changing characteristics of the problem, resulting in an efficient solution procedure. A large scale unit commitment problem solution is further reported [89] in which the optimization model developed incorporates all practical constraints. A solution methodology has been developed for the optimization model that has two unique features; (1) Computational requirements grow linearly with number of units, and (2) Performance of the algorithm improves as the number of the units increased. Cohen and Yoshimura [90] have included the probabilities reserve constraint along with time dependent startup cost and assumed no priority ordering for the solution of the UC problem.

1.6.7 Lagrangian Relaxation

Lagrangian Relaxation (LR) optimization technique decomposes the UC problem into a master problem and subproblems that are solved iteratively until a near-optimal solution is reached. The problems are solved independently. Each subproblems determines the commitment of a single unit. The problems are linked by Lagrange multipliers that are added to the master problem to yield a dual problem. The dual problem has lower dimensions than the primal problem and is easier to solve. The primal function is always greater than or equal to the function which is defined as weak duality. The difference between the two functions yield the duality gap. The duality gap provides a measure of near-optimality of the solution.

The Lagrangian multipliers are computed at the master problem level. Once computed the Lagrange multipliers are passed to the subproblems. The solution of the subproblem is fed back to the master problem and updated multipliers are obtained and used by the subproblem again. This process is repeated until solution converges. For a large scale problem, the solution is presented by [96]. They followed the traditional formulation of the problem which gives rise to the large scale dynamic, mixed integer programming problem. They described methodology based on duality. Lagrangian relaxation and non differentiable optimization has two unique features; firstly, the computational requirements typically grow only linearly with number of generating units; and secondly, the duality gap decreases in relative terms as the number of units increases. As a result the algorithm tends to actually perform better for problem of large size. This allows for the first time consistently reliable solution of large practical problems involving several hundred of units within a realistic time constraint. Apart from the UC problem, this methodology is applicable to a broad class of large scale dynamic scheduling and resource allocation problem involving integer variables. A. Merlin et al [97] have given survey of work reported and have presented new contribution where LR can solve completely large scale UC problem. Their method has the flexibility to include pumping units and probabilities determination of the spinning reserve. The paper brings new contribution towards detailed description of duality difficulties and new algorithm to update Lagrangian multipliers. The methodology is defined in an conventional manner to include all practical constraints. The method is based on the observation that if selected commitments satisfy system capacity and reserve capacity constraint, then it is to determine via economic dispatch, a generation schedule that would satisfy given demand. The method simplifies the procedure for searching the feasible solution near the dual optimal, but cannot promise the true optimal solution. A more advanced UC method is proposed which can be implemented in system with fuel constraints. For some utilities, contractual or other factors limit the amount of fuel available to certain units or plants. A.I. Cohen et al [98] has developed method which solves UC problem along with fuel constrained plants. The method uses Lagrangian decomposition and successive approximation techniques where generation reserve and fuel constraints are adjoined into the cost function using Lagrangian multipliers. A. Akoi et al [99] presented an algorithm which also deal with fuel constraint plants along with pump storage hydro plants. As compared to Cohen's work in which submargined method is used for upgradation of multipliers, Akoi has used variable metric method to upgrade multipliers for maximizing Lagrangian function.. The method is applicable to a realistic size system. F. Zhuang et al [100] presented an algorithm which solves UC in three phases. The phase bound method sequentially provides solution near to optimal solution. A supplement to the above method is presented by Tong et al [101] Along with LR, they used linear programming for obtaining the solution. Their approach employs the LR to determine a feasible suboptimal schedule and then Llinear Programming is applied to improve the feasible solution. The method is claimed to be more efficient than Dynamic Programming. Implementation of LR method has been explained by S.Virmani et al [103]. He has attempted to provide a mathematical formulation of the UC problem, justified LR methodology as a solution technique and finally provided a detailed account of the practical computational steps needed to apply the technique. In earlier implementation of LR method with fuel constrained unit used only one fuel. But with multiple fuels supplying a unit may increase the complexity of the UC problems because the fuel price at a unit may not be readily available. S.Vemuri et al [106] has proposed the solution of such complex problem using LR method. The fuel constrained UC problem is decomposed into a linear fuel dispatch (FD) problem and a UC problem. The FD problem optimizes system fuel cost while satisfying fuel constraints and unit fuel requirements including effective pricing at a unit. The solution process iterates between UC and FD until no further cost improvement is possible. The use of ramp-rate constraint to simulate the unit state and generation changes has a strong effect on optimal scheduling. In their previous work, Wang et al [107] have used dynamic adjustment method for inclusion of ramping constraints in generation scheduling. In their proposed iterative approach to generation scheduling, LR method is used for UC with energy balance constraints. The usual criteria for convergence is applied, that is, the difference between the original problem and dual problem to be within limits and then Linear Programming is used for the power dispatch by incorporating the cost of replacing rotor shaft due to torque effect. Application of ramp-rate effect is later included in their work by W. Peterson et al [108]. They suggested extention to incorporate unit minimum capacity constraints and ramp-rate constraints, based on work by Virmani [103]. The introduction of unit ramp-rate constraint requires modification of the calculation of capacity constraints and reserve constraints. The algorithm incorporates other practical features such as boiler fireup characteristic and non-linear ramp sequence. Ruzic et al [105] have presented a unique approach to UC. In earlier work ramp-rates were considered in the simplified heuristic manner. However, Ruzic et al have incorporated ramp-rates into a dual optimization algorithm giving rise to a possibility of application of feasible direction method for primal problem solution. The method also includes transmission capacity limits, regulation reserve requirements of prespecified group of units, transmission losses and fuel constraints along with standard constraints. Subsequent application of LR and Lagrangian decomposition have added various considerations to the basic formulation of UC. However, still certain issues are required to be considered that affect power system operation. Earlier papers assumed that, commitment and dispatch of hydro resources have already been determined apriori so that thermal generators are then used to meet the total demand excluding hydro production. Hydro generators usually ramp very quickly so that they may be particularly valuable resources at times when the demand is changing rapidly. The papers searched so far included certain hydro, gas constrained units but the line flow constraints and voltage constraints are not covered. Ross Baldick [111] have attempted to include all issues referred above. As system becomes more constrained by line flows and voltage constraints, the generation level determined by optimal power flow will deviate more from the generation level suggested by UC program, unless these constraints are also included in UC program itself. The methodology termed as ' Generalized Unit Commitment Problem' have used Lagrangian decomposition technique and thus demonstrated the usefulness of the technique. The above technique, however, didn't include an alarming issue, that is, pollution caused by thermal system. Fossil fuel fired thermal units have an impact on air quality of region owing to the emission of SOx and NOx gases. The clean air Act [49] enacted in USA and similar acts imposed by other countries and awareness of pollution effect on human beings have prompted to include Sulphur and Nitrogen Oxides constraints in power generation strategies. Minimum emission dispatching, unlike conventional dispatching, minimizes the emission function but increases operating cost. To overcome this problem, emission function is added as a second objective resulting in units with high emission to generate less power and thus emissions are reduced. S. Kuloor and G.S. Hope et al [125] have attempted UC with emission constraint. The aim of the UC is naturally to select the units to operate for longer time and with reduced emission. The method describes the use of LR procedure with multiple decomposition. The variables of load, reserve and fuel constraints are adjoined to the objective function using Lagrangian multiplier. Emission function is used as a second objective function. This multiple-objective minimization problem is converted into a single-objective minimization problem by considering a new objective function which is a weighted sum of the two objective functions. The method is quite fast and can handle large systems.

1.6.8 Expert System/Artificial Neural Network

Expert system combines the identification of existing problem with the UC algorithm and knowledge of the experienced power system operators and UC programming experts to create an expert system rule base. Estimates of the Artificial Neural Network(ANN) parameters are based on database to select the most economical UC schedule.

Susan Mokhtari et al [109] has introduced expert system in UC. Execution of the UC program requires a large amount of data setup and initialization. Some of the data involved are heuristic and a small change in the heuristic data often causes a large change in the results. On the other hand, despite the use of sophisticated programs, it is not always possible to obtain a schedule which is operationally acceptable. Their paper [109] presents the experience of the author in setting up the expert system which combines the knowledge of the UC programme and an experienced operator. Using base commitment by DP, a method is developed by Md. Sayyed Salam et al [112]. This uses an expert system as preprocessor as well as post processor to the truncated DP based unit commitment to obtain an operationally feasible and/or preferrable solution. The operator's interaction with the expert system is minimized by transferring all the relevant data and results of the UC program to the expert system as knowledge base. Computer software simulations of neural network and various expert system shells have provided powerful tool for developing new system. The neural network computing enhanced by expert system has opened novel route to the optimization of generation scheduling. With proper and sufficient offline training, the information regarding the optimal operation of a system can be stored in the network and the output is obtained in a much shorter time. The work by Z. Yoyang et al [113] have proposed short term UC which employs a multistage neural network - expert system approach to achieve real processing results. The operating constraints are presented as heuristic rules in the system where a solution is obtained through inference. The neural networks are used at preprocessor and postprocessor stages. At the preprocessor stage, load matching scheme is performed and at the postprocessor stage, a trained neural network performs considerable adjustments to achieve the optimal solution. H Sasaki [115] has explored the possibility of applying the Hopfield neural network to combinatorial optimization problem in UC. Number of inequality constraints included in UC are handled by dedicated neural networks. Further, they have developed a two step solution method; firstly, generators to startup at each period are determined by the network; and secondly, their outputs are adjusted by a conventional algorithm. A hybrid method of Dynamic Programming neural network (DP-ANN) is studied by Z. Ouyang et al [116]. They used artificial neural network to generate preschedule according to the input load profile and then dynamic search is performed at those stages where commitment states of some of the units are not certain. Genetic Algorithm (GA) represents a class of general purpose stochastic search technique which simulate natural inheritance by genetics and the Darwinian ' survival of the fittest' principle. The GA's are increasingly being applied in a variety of search optimization and scheduling problems across a wide spectrum of discipline. Even though ANN based Expert system methodology have demonstrated some improvement in solving UC problem,these methods however require a lot of operator interaction which is troublesome and time consuming for even a middlesized utility. Genetic Algorithms are different from the classical methods in three ways- (1) They work with coding of the parameter set rather than the actual parameters and work equally well with discrete and continuous function; (2) They search from a population points; and (3) They use probability transition rules. In their work, D. Dasgupta et al [117] have used GA to thermal UC. The paper discusses the application of GA to determine short-term UC of thermal units. They have used simple genetic search technique to determine optimal or near-optimal commitment schedule. In their algorithm, the program starts with a random initial population and computes fitness of each individual(commitment decisions) using the forecasted load demand and operating constraints. Each time the genetic optimizer is called, it runs for a fixed number of generations. Even though the cell works well with conventional cost functions and constraints, the disadvantage of this approach is the computation time needed to evaluate the population in each generation. Approach by S.A. Kazalis et al [118] uses varying quality function technique to obtain satisfactory solution to UC. Another approach is reported by T.T. Maifield et al [132]. They attempted to reduce the time required for GA based algorithm by using domain specific operators. Due to inexact load forecast, the demand in MW cannot be deterministic. Therefore, the optimization of the daily generation schedule is inherently stochastic in nature. For example, in country like France [117] a temperature variation of one degree Celsius leads to a variation of demand more than 1000 MW. Moreover, due to failure of certain units, planned schedule may be disturbed, hence the notion of 'spinning reserve' is introduced. This power margin may be used within stipulated time. Because of this reserve availability, the operator is able to face the most unusual random disturbances. Moreover, due to this margin available for appreciable time (hours), it allows time to startup other units in order to build up an adequate level of reserve again. The deterministic approach with reserve constraints is used in practical fields; however, global optimum cannot be ensured this way. Carpentier et al [122] have attempted to achieve solution of a problem which is stochastic in nature. In their approach, random disturbances are modelled as scenario trees. Optimization consists in minimizing the average generation cost over this 'tree shaped future'. The augmented Lagrangian technique is applied to this problem. At each iteration, non-separable terms introduced by augmentation are linearized for each unit and a stochastic dynamic subproblem is solved. Prices attached to nodes of the scenario tree are updated by the coordination level. According to Carpentier, stochastic approach provides a better alternative to the spinning reserve method. Another approach to the UC is reported by Samer Takriti et al [123]. In their work, uncertainty in the demand is modelled by choosing a set of possible scenario. Each scenario is assigned a probability that reflects its likelihood of occurence. The model problem is solved by LR. As per authors' experience, the stochastic model can reduce the cost.

1.7 Motivation

Generation scheduling or dispatch is very important aspect of power system. Right from beginning of power system era, researchers are developing or presenting techniques so as to minimize cost, satisfying all relevant constraints. Thermal plants are represented by input/output curves. These curves may be modelled as linear [2, 20], quadratic or polynomial of higher degree. However, most of the researchers use linear or quadratic model. Linear model or linear cost function along with linear constraints leads to linear programming application for generation scheduling or unit commitment [8]. Invariably, quadratic cost functions are being used by most of the researchers. For generation scheduling various methods are developed. Lagrangian multiplier method [6] is most popular and is very easy to implement. Other methods in use are Gradient [8,129], and dynamic programming [35]. Hydro system are represented by discharge functions in the form of linear or quadratic equations. Mostly gas plants are operated on take-or-pay basis. Naturally, volume available is fixed and its cost is also fixed. These plants' consumption functions are also quadratic or linear. Representation of various plants by specific functions is necessary for coordination among the plants pertaining to the same area or other areas. Now in estimating generation schedule, two aspects are required to be taken into account. One, at plant level and that second at system level. At plant, allocation of generation can be estimated by the methods mentioned above. But at system level generation allocation is estimated [27, 28, 29, 30] using equivalent cost function. Having obtained plant generation, again generation allocation is calculated for all units at plant. Representation of plant by equivalent cost functions, particularly quadratic cost functions are developed by [27, 28, 29, 30] using basically Lagrangian multiplier technique. A curve fitting technique [8] is also developed but the same is approximate and naturally do not provide accurate total cost at plant level. While estimating allocation, certain units may violate their bounds. Hence, to include this aspect, cost functions are corrected [22]. The correction method [22] is very accurate and easy to be included in the program. The attempt by Nityananda et al [27] is very complicated and large numbers of variables are introduced. Generation scheduling technique developed [13 to 19] are basically derived from Lagrangian multiplier. However, an attempt by [22] using zoom features have applied Dynamic Programming and used cubic cost functions. Hydrothermal coordination with inclusion of transmission losses is basically an iterative procedure. Such methods are based on linear programming, dynamic programming, gradient method and Lagrangian multiplier [8]. Method developed by [35] uses DP with a tacit bound on rise of generation on units due to transmission losses. In environmental dispatch problem, attempts are made to maintain emission level to specified level [52, 53]. As far as India is concerned, plant location is a very important factor. With due respect to techniques developed so far by different researchers for maintaining emission level at specified level at system level, it is also necessary to maintain emission level under control at plant level. At plants, type of units, types of fuels being used, the pollutants emitted by each unit may have different characteristics. However, in most of the works, plantwise emission functions are used and attempts are directed towards minimization or trade-off at system level. Location of plants near highly polluted site may be imposed with different emission level as compared to a plant situated far away from polluted area. Hence, it is necessary to take into account plantwise emission level for environmental and economic dispatch.

So far many techniques are presented for Unit commitment. Exhaustive enumeration is attempted for thermal as well as for hydrothermal units. Priority list [63] is also being used but very few utilities have accepted it in toto. However, it is being used [63] for UC along with Dynamic Programming [70] . The priority list method is corrected by Lee [65] by introducing Commitment Utilization factor (CUF) and the same is tacitly [66] being used for multiarea unit commitment. Lowery [67] was first to introduce Dynamic Programming for unit commitment and to date many methodologies and forms of DP are presented. However, DP suffers from the curse of dimensionality. To reduce dimensionality, priority of units is incorporated. To solve large size problems, DP along with priority list method is attempted. Guy [68] has proposed secured UC by introducing reliability aspect. Solution of large size problem is attempted by successive approximation and hierarchical approach. Recently, expert system as well as Neural network are also being used along with DP for UC. It is observed that DP is also being used along with LR method for solution of large size UC problems. However, of all the above methods very few have taken into account [111] grouping of units. Most of the work on UC are attempted for thermal system and very few have incorporated [111] hydro or gas units. Due to Clean Air Act, of 1990 of USA [49] and similar acts by other countries, and awareness to protect environment researchers are encouraged to include control of emission in UC program. As far as LR is concerned, it is gaining importance and practically all aspects are taken into account. Presently, the trend is to use Neural Network for UC. However, researchers are still using DP technique at preprocessor stage. Having gone through all the methods surveyed so far , it is observed that DP technique is widely used. However, no researcher so far reported the UC using equivalent cost function developed for a group of units. Moreover, researchers [63, 65] have applied AFLC for making priority list used for UC but no researchers have reported priority list made using equivalent cost function. Moreover, solution using DP is not presented for mix system including emission constraint. In view of the above facts, the following aspects are considered for research using recursive technique of Dynamic Programming.

- Derivation, in a very simplified manner, of equivalent cost function which may be used to estimate generation cost directly.
- Development of algorithm for generation scheduling of thermal system including transmission losses and also generation scheduling for multiarea and for multifuel system.
- Development of an algorithm for mix-generation system.
- Development of emission constrained dispatch taking into account plantwise emission constraint.
- Development of merit ordering or priority list of units and order of combination of units along with range of operation.

- Development of generalized algorithm for short-term unit commitment for thermal, mix-generation along with emission constraint.

1.8 Thesis Organization

Chapter 1 introduces the concept of unit commitment and generation scheduling and presents a brief survey of research work carried out in this area.

Chapter 2 is devoted to the derivation of basic formulation of equivalent cost function and load allocation on units, using Dynamic Programming. Generation scheduling is performed for single fuel units, with and without transmission losses. The work is further extended to find generation scheduling for units with multiple fuel options.

Chapter 3 presents hydrothermal, thermal-gas and mix-system generation scheduling with and without transmission losses using Dynamic Programming.

Chapter 4 reports preparation of merit ordering of thermal units using equivalent cost function and preparation of unit commitment table for single fuel and multifuel units.

Chapter 5 presents economic and environmentally efficient dispatch with local constraints.

Chapter 6 is devoted to unit commitment of a thermal and mix-system using DP along with emission constraint.

Chapter 7 concludes the main findings and summarises significant contribution to the existing literature by the author, and also mentions a few suggestions for carrying out further research work in this area.