CHAPTER 1

INTRODUCTION

1.1 POWER SECTOR SCENARIO

Electrical energy occupies the top place in the energy hierarchy and it plays a vital role in economic growth and industrial development of any nation. The per capita energy consumption of electricity is an index of prosperity of the people in the nation. The sustained economic development in India has created a need for additional power generation capacity. The Central Electricity Authority (CEA) of India has indicated that, the level of electric power generation would be 85% only in the total installed capacity of about 2,37,742.94MW and leaving a gap of about 35,661MW in demand as on 28.02.2014. Hence, the Indian power sector is facing challenges to cope up with demand and energy requirements.

Out of the total existing power generation capacity, around 68% (CEA Report) is contributed by thermal power. With a need for sustainable economic growth, the Government of India is encouraging and catalyzing the growth of renewable energy based electric power including biomass, wind, hydro, solar photo-voltaic etc through the Ministry of New and Renewable Energy (MNRE) and Ministry of Power (MoP). Also, the MoP has set a goal ‘Power for All’, in which one of the strategies to achieve the goal is Power Generation Strategy. It focuses on low cost generation, optimization of capacity utilization, controlling the input cost, optimization of fuel mix, technology up-gradation and utilization of renewable energy sources. Thus,
there is huge scope of renewable energy sources for increasing the power generation capacity to meet the demand of Indian power sector.

In recent years, wind energy is rapidly becoming a power generation source of significance and is one of the most promising alternative energy of the future. As of 2013, statistical report of Global Wind Energy Council (GWEC) says that the total installed capacity of wind energy generation is about 318.14GW world-wide and nearly 19% is contributed to the total power generation. China is having the highest installed capacity of wind power generation of about 91.42GW followed by USA, Germany, Spain and India. Globally, India ranks 5th in position with an installed wind power capacity of about 20.15GW. In terms of wind energy integration with existing electric power generation, India is ahead with 3 to 4% penetration while USA and China are having ~3% and ~2% respectively (CWET 2012).

1.2 ELECTRIC POWER SYSTEM RESTRUCTURING AND DEREGULATION

For many decades, the vertically integrated monopolistic power industries dominated in most of the electricity generation, transmission and distribution of the power sector. The objective of generation part of electric utilities is to produce power and should satisfy their customers with minimum production cost. During 90’s, many electric utilities and power network companies world-wide have been forced to change their ways of doing business, from vertically integrated mechanisms to open market systems. The electric power can be sold for marketing as and when it is produced but cannot be stored. Deregulation is the new paradigm in electric power sector and implementing the modifications in existing regulations and structure of power industry to create a competitive power market.
A typical structure of a regulated power system (vertically integrated utility) is shown in Figure 1.1, where the links of information flow existed only between the generation and the transmission system. Similarly, money flow was unidirectional, from the consumer to the electric utility. The operation and control issues for the regulated power system have been widely examined over the years. The basic objective of such a system would be to minimize the total operating cost while satisfying all associated system constraints. Apart from the operational issues, it has a centralized system of planning for the long-term. All activities such as long-term planning like expansion of generation and transmission, medium term planning activities like maintenance, production and fuel scheduling were coordinated centrally. One of the first steps in the restructuring process of power industry was the separation of transmission activities from the generation activities. The subsequent step is to introduce competition in generation activities, either through the creation of power pools or bidding in the spot markets.
The structure of deregulated power system is shown in Figure 1.2, where the links of information flow and money flow existed between almost all the players. This is not a universal configuration and there exist variations across countries and systems. The possibility of having such a complex nature of information flow has been one of the driving factors in the process of deregulation of the power sector. In the restructured system, the main tasks of generation, transmission and distribution remain the same as before. However, new types of unbundling, coordination and rules are established to guarantee the competition and non-discriminatory open access to all users in the interconnection (Bhattacharya et al 2001).

Restructuring the electric power industries is a very complex exercise based on national energy strategies and policies, macroeconomic developments and national conditions, and its application varies from country to country. There are many terms available to represent the restructuring process and the commonly used terms are: liberalization, deregulation and privatization. All these terms are processed under the general label of market reform.

Figure 1.2 Structure of deregulated power system (Bhattacharya et al 2001)
In deregulated power system, the ownership of vertically integrated power industries are divided into three major groups such as Generation companies (Gencos), Transmission companies (Transcos) and Distribution companies (Discos), with a central coordinator, called an Independent System Operator (ISO), to balance supply and demand in real time and to maintain system reliability and security. The primary objective of ISO is to match the electricity supply with demand. At the same time, ISO must control power generation to the extent required to maintain reliability, optimize transmission efficiency, and maintain stability of the power system (Lai 2001).

**Gencos:** A Genco is a regulated or non-regulated entity depending upon the industry structure that produce and sell electricity. Genco may refer either to individual generating units or to a group of generating units within a single company ownership with the objective of producing power, and commonly referred as Independent Power Producers (IPP). Gencos have the opportunity to sell electricity to the entities with which they have negotiated sales contracts. In addition to real power, Gencos may trade reactive power and reserve power.

**Transcos:** A Transco is an entity that transmits electrical power using a high-voltage, bulk transport system from Gencos to Discos for delivering electrical power to the customers. Transco is composed of an integrated transmission network which is shared by all participants. Also, its radial connections link the generating units and large customers to the network. In some systems, the Transcos are classified according to the operating voltage levels, such as National Transcos (at 400 KV and 220kV), Regional Transcos (at 132 kV), etc.

**Discos:** A Disco is an entity that distributes the electrical power to the customers through its facilities and operating the local distribution network in an area. A Disco constructs and maintains the distribution wires with certain
degree of reliability. Discos must coordinate their functions with Transcos and ISO to ensure the power flow. In addition, a Disco buys wholesale electrical power either through the spot-markets or through direct contracts with Gencos.

**ISO:** The ISO is an entity entrusted with the responsibility of ensuring the reliability and security of the entire system. It is an independent authority and does not participate in the electricity market trades. ISO usually does not own generating resources, except for some reserve capacity in certain cases. With the intention to maintain the system security and reliability, the ISO acquires various services such as supply of emergency reserves or reactive power from other entities in the system.

**Customers:** A customer is an entity having several options for consuming and buying electrical power in deregulated markets. They may choose to buy electrical power from the spot-market through bidding, or may buy directly from Gencos or even from the local Discos.

**Retailers:** The retailer is an entity responsible for the operation of the electricity market trading. It receives bid offers from market participants and determines the market price based on the criteria in accordance with the market structure. The markets may have different trading schemes such as hourly trading for the next day or trading in futures- weeks, months or years ahead.

### 1.2.1 Restructured Electricity Markets

The deregulated electricity market has three main distinct models such as PoolCo Model, Bilateral Contracts Model and Hybrid Model.
**PoolCo Model:** A PoolCo is a centralized marketplace that clears the market for buyers (customers) and sellers (suppliers) where the electrical power sellers and buyers submit their bids to inject power into and out of the pool. Sellers compete for injecting power into the grid, not for specific customers.

**Bilateral Contracts Model:** The bilateral market is one in which trades (quality and price) are determined directly between suppliers and customers without interference from ISO (Shahidehpour & Alomoush 2001). In the bilateral trading, the ISO’s role is more limited; and the buyers and sellers could negotiate directly in the marketplace.

**Hybrid Model:** Most of the wholesale electricity markets have the characteristics of both PoolCo and bilateral models. The hybrid model provides the maximum flexibility to the customers for purchasing electrical power either from the pool or directly from the suppliers.

Moreover the other significant restructured electricity market characteristics such as market timing, scheduling and ancillary services are required for the reliable operation of the power system. The ancillary services are the functions performed to support the basic services of generating capacity, energy supply and power delivery. The electricity markets can be characterized at different time scales: year ahead, month ahead and day ahead are called Forward electricity markets, which run in advance of the delivery time. On the other hand, the markets that are operating in the order of minutes in advance of delivery time are called real-time markets.

The trend of deregulation around the world reformed the power sectors and the deregulated electricity markets are however not uniform in all the countries. Historically, the Latin America, in fact, Chile though not as well known as the UK, was the real pioneer of radical restructuring in 1982. The first step towards deregulation of the power sector was taken by the
enactment of the state reformation law of 1989. Followed with this act, England and Wales implemented liberalization for consumer of 1000kW and privatized the national electric utilities in 1990.

Several South American companies started deregulation laws in line with the Chilean initiatives, Argentina in 1993; Peru in 1994; Bolivia and Columbia in 1994; Brazil in 1998 and Mexico in 1999. The status of retail liberalization varies from state to state and the open-market operation was commenced in Norway two years after the passage of the Energy Act in June 1990. Though the United States electricity market Act was promulgated in 1992, the electricity restructuring is being undertaken state by state. The Swedish market reform was taken in 1991, with the decision to separate transmission from generation. Wholesale electricity markets were commenced by New Zealand in 1993; Australia in 1994; Finland in 1995 and California started the commercial operation in 1998. Japan introduced the competitive bidding on generation capacity in 1996.

The Spanish and German electricity markets implemented a new electricity Law in 1998. The deregulation process is being undertaken in France through a progression of laws in February 1995. The Brazilian wholesale energy market was created in 1998 on the basis of auction mechanism on the generation. In mid 1990s, Orissa was the first state in India to begin the fundamental restructuring process in state power sector (Shahidehpour et al 2002). Through the Electricity Act of 2003, the other states of India such as Andhra Pradesh, Haryana, Uttar Pradesh and Rajasthan were moved towards creating a market based regime in the power sector. Recently, TamilNadu Electricity Board in southern region of India was restructured in the year 2008. Similarly, several other countries are developing the process of deregulation in power sector.
1.3 UNIT COMMITMENT PROBLEM IN REGULATED AND DEREGULATED ENVIRONMENT

In electric power generation, the problem of optimal operations and planning of power systems is one of the most important optimization problems. Electric power consumption will be generally higher during the daytime and early evening when industrial loads are high, lights are on and so forth, and lower during the late evening and early morning when most of the population is asleep. In addition, the electric power demand being higher over weekdays than weekend days. Therefore, predicting the load demand and preparing the generators ON/OFF schedule can save a lot of money for an electric utility. To commit or turn ON a generating unit means to bring that unit to the rated speed, synchronize and connect it to the system. So the generating unit can deliver power to the network. The problem with ‘commit enough generating units and leave them on line’ is one of the major economics in power generation. This problem is known as Unit Commitment Problem (UCP). Economic Dispatch (ED) is defined as the process of allocating generation levels economically within their limits while satisfying the system and generator constraints (Sen & Kothari 1998). But, the UCP is the advance step of ED problem where the decisions of committing or de-committing a generator have to be taken. The UCP is much more complex to solve, compared to the ED problem, due to the presence of binary decision variables on the generating unit ON/OFF status (Steven stoft 2002).

For the vertically integrated monopolistic environment in the past, Unit Commitment (UC) is defined as scheduling the on/off status of generating units in order to minimize the total production cost of utility over the scheduled time period, when subjected to the existing constraints (Sheble & Fahd 1994).
In traditional system electric utilities had an obligation to serve their customers that all demand and spinning reserve must be completely met, but this is not necessary in the restructured system. For a ‘N’ generating units configuration as shown in Figure 1.3, the fuel inputs $F_1, F_2, \ldots, F_N$ are given to the turbines which rotate the generators. The summation of all the generated powers $P_1, P_2, \ldots, P_N$ should meet out the demand $P_D$ in traditional UCP (Wood & Wollenberg 1996).

1.3.1 Thermal Profit Based Unit Commitment Problem

As the power industry is open to competition, many of the traditional algorithms for power system operation, planning and control aspects need to be revised. In deregulated environment, unit commitment is considered by the system dispatching center and Gencos. The Gencos are trying to schedule their generating units according to the operating conditions of their generating units and other economic factors. These objectives of Gencos make their generating units to have longer possible life span and for profitable power production. Hence, each Gencos make their own UC schedule separately. The UCP under deregulated environment is more
complex than traditional unit commitment. In deregulated power system, the UCP has a different objective than that of UCP in a traditional system. They may choose to generate less than the demand, which allows more flexibility in unit commitment schedules. Therefore, redefining the UCP for deregulated environment involves changing the demand constraints from equality to inequality (less than or equal to). Also, the objective function is modified from cost minimization to profit maximization. Based on the forecasted power/reserve prices and load demand/reserve, Genco can consider a schedule that produces less than the predicted load demand and reserve. Also, it produces maximum profit. This problem is referred as Profit Based Unit Commitment (PBUC) problem. It is much more difficult to solve than traditional unit commitment problem and plays an essential role to maximize the profit of Gencos (Padhy 2003).

The PBUC problem is one of the important combinatorial optimization problems in restructured power systems and it determines the generating unit schedules over the specified time period for maximizing the profit of Gencos subject to all prevailing constraints such as load demand, spinning reserve, ramp rate limits, etc.,.

![Figure 1.4 Schematic of profit based unit commitment](image-url)
The schematic representation of PBUC is shown in Figure 1.4, where the individual Gencos run its unit commitment to schedule the generation units in order to maximize their own profit. Minimizing the cost is not always equivalent to maximizing the profit, since the profit is the difference between revenue of selling power and the cost of producing power. Besides, the market energy price signal is crucial for PBUC, since it defines the revenue. Each generating unit of Genco has its own technical constraints depending upon the generation type such as coal, wind, hydro, PV, etc., For instance, wind generation units are subject to wind fluctuation constraints and wind power curve defines the output power of wind turbine generator. The wind unit generation should be scheduled by considering the wind speed limitations. Thus the various power generating units have their own constraints specifying the technical and physical characteristics.

1.3.2 Wind-Thermal Profit Based Unit Commitment Problem

The impacts of wind power on power system operation, comprise different time scales ranging from seconds to weeks. On the shorter time-scale (ranging from seconds to minutes) wind power has a direct impact on system frequency for the power balance between generation and load. Primary and secondary reserves are used for maintaining this balance. On the longer time-scale (ranging from hours to weeks) wind power influences the economic dispatch and commitment of conventional generation units. Presently, conventional generation plays a vital role in maintaining the power balance between generation and demand. Among the renewable energy sources such as wind, solar, biomass, tidal, geothermal, etc., wind energy has the huge potential to play an important role in energy market along with conventional energy sources. In India, wind power achievement is 1267 MW but the solar power is only 47MW in the year 2013 (CEA Report 2014). Also wind power has tremendous environmental and social benefits than other energy sources.
Figure 1.5 Schematic of wind-thermal system

An illustration of a Thermal Generator (TG) and Wind Generator (WG) system serving a common load PD is shown in Figure 1.5. The output of wind turbines cannot be controlled as conventional generation technologies, due to the variability and limited predictability of the wind speed (Chen 2014). Moreover, the power generation cost of WG from the public utility is the cheapest because it needs no fuel, but in a privately owned non-utility, the cost of wind power generation has been based on the economic schedule for buying or selling energy between each Independent Power Producer (IPP) and the public utility. IPPs will be a major driver of the wind power market in India. IPPs accounted for about 25% of all wind capacity installations in the financial year 2012-13 and have a project pipeline of almost 16 GW. Also, IPPs have been helped to establish other project financing agencies like Indian Renewable Energy Development Agency (IREDA), Power Finance Corporation and Rural Electrification Corporation (CWET 2012). Thus, the increasing penetration of wind energy requires some new technical and economical challenges to power system operators in deregulated electricity markets.

The scope of unit commitment problem is varying from one utility to another utility due to the type of generating units and its operating constraints. The PBUC problem in deregulated environment is challenged by
wind power due to the uncertainty in wind power generation. Also, the economic consequences of generation scheduling in electricity markets are very important. Since the inclusion of wind energy reduces the thermal unit fuel cost by a little, it can result in savings of millions of dollars per year for large utilities (Yamin 2004). Thus the UC models need to change in order to integrate thermal generation with wind power generation.

A number of challenges arise when integrating wind energy into the conventional power system such as resource adequacy, interconnection standards dealing with the increased uncertainty and variability in short-term operations and transmission planning, etc., (Billinton & Bai 2004). These wind power challenges are compromised in two ways. One of the ways is that the presence of wind power for longer time periods reduces the output level and/or operating hours of the conventional generation units which may be scheduled and made available for load balancing purposes. The other way is that wind power introduces additional variations and uncertainties, which are typically handled with additional operating reserves. In deregulated electricity markets, an additional type of ‘operating reserve’ is proposed as shown in Figure 1.6. This reserve might be less expensive than the traditional emergency reserve.

![Figure 1.6 Relationship between system operating reserve and uncertainty (Botterud et al 2013)](image-url)
Besides, the existing operating reserve requirements and procedures, must be enhanced in such a way that it includes: (i) Control of the output of wind power generation effectively during constrained system conditions. (ii) Wind power to be represented in the real-time market with price/quantity bids to obtain an efficient dispatch and schedules (Botterud et al 2013).

1.4 LITERATURE REVIEW

Unit commitment is the most significant optimization task in the operation of deregulated power system. Solving the PBUC problem for large scale power systems is computationally expensive, because the complexity of the problem grows exponentially to the number of generating units. Several solution methods have been proposed to provide optimal solutions to the unit commitment problem in restructured environment and increase the potential savings of the power system operation. This section presents a summary of research work, which was carried out so far. The techniques normally used to solve the PBUC problem are Deterministic, Artificial Intelligence and Hybrid approaches.

1.4.1 Deterministic Approaches

The deterministic approaches that have been reported in this context, are Priority List (PL), Dynamic Programming (DP), Mixed Integer Programming (MIP) and Lagrange Relaxation (LR) methods.

1.4.1.1 Priority list method

Burns & Gibson (1975) have presented a straightforward and computationally efficient algorithm using priority order of generating units for solving UCP. Sheble (1990) has proposed the unit commitment method in such a way that base load units are committed first and then peak load units
are committed last, based on the order of priority of units, in order to meet the load demand. This method produced the schedules with relatively high operating costs.

Senjyu et al (2003) have introduced extended priority list method with two steps. The initial UC schedules were produced by priority list method and then modified using the problem specific heuristics to satisfy the unit and system constraints. Then only the economic dispatch was performed on the feasible schedules and it drastically increased the convergence time.

1.4.1.2 Dynamic programming

Lowery (1966) has proposed the Dynamic Programming (DP) to solve UCP with the aim to determine the feasibility and practical applicability of DP method. The results of case study represented that simple and straightforward constraints were adequate to produce an optimum operating policy with less computational time. Though the DP method was flexible, the drawback was the ‘curse of dimensionality’, which increased the mathematical complexity and computation time if more constraints were considered. Hobbs et al (1988) have developed an enhanced DP approach to a realistic UC model in an on-line energy management system. A merit order list was formed which excluded all unavailable, fixed output, peaking, and must run units. Subsequent combinations of units were formed by de-committing one unit at a time. This method formed several states from each unique combination and linked each state to one of the other possible paths to that combination.

Valenzuela & Mazundar (2001) have presented a new formulation of UCP suitable for an electric power producer in deregulated markets. In this market, the objective of the system operator was maintenance of the system security and maximization of its own profit. Andy & Rudiger (2006) have
studied the UCP from the perspective of a generator allocating strategy. It offered to an electricity pool market by stochastic dynamic programming to construct the optimal schedule in successive time periods over a fixed planning horizon. Chen (2008) has proposed branch and bound based dynamic programming algorithm to coordinate the wind and thermal generation scheduling problem for operating an isolated hybrid power system. Because of the intermittency and unpredictability of wind power generation, additional physical and economic operation constraints have been considered to reach the system security and total production cost.

### 1.4.1.3 Mixed integer programming

Dillon et al (1978) have developed an Integer Programming method for scheduling problem of practical electric utilities. The UCP was partitioned into a nonlinear economic dispatch problem and a pure integer nonlinear UC problem based on Benders approach. Mixed integer programming approach solved the UC problem by reducing the solution search space through rejection of infeasible subsets. Ruiz et al (2009) have developed a stochastic model to manage the wind power uncertainty in the UCP. The stochastic model was considered as the alternative to the traditional deterministic approach, which captured several sources of wind uncertainty and defined the system reserve requirement for each scenario.

Bisanovic et al (2012) have presented the self-scheduling model for generation companies having thermal power units. The self-scheduling model was formulated as deterministic optimization problem considering bilateral contracts and day-ahead markets, in which expected profit was maximized by 0/1 mixed-integer linear programming technique. This approach permitted only the precise model of variable costs, start-up costs and comprehensive system of constraints.


1.4.1.4 Lagrange relaxation method

Merlin & Sandrin (1983) have implemented a technique for solving UCP by Lagrangian Relaxation method. This method used the Lagrange multipliers and provided solution to the UCP of Electricite De France system. Peterson & Brammer (1995) have proposed a Lagrange Relaxation method to solve UCP with unit minimum capacity and ramp rate constraints. The proposed method was implemented to find a feasible UC schedule considering ramping constraints. Ongsakul & Nit (2004) have introduced an enhanced Adaptive Lagrangian Relaxation (ALR) approach. It comprised of heuristic search and adaptive LR to solve UCP. Though this method provides faster solution, it failed to obtain solution feasibility and becomes complex if the number of units increased. Li Tao & Shahidehpour (2005) have formulated the price-based unit commitment problem of a generating company. It comprised of cascaded-hydro, thermal, pumped storage and combined-cycle generating units. The major difficulty of this paper was more computation time and huge memory requirement to solve large scale UC problems. Yamin et al (2007) have presented a new LR approach for PBUC problem in day-ahead competitive electricity markets. The authors estimated the probability for spinning and non-spinning reserve uncertainty using Lagrangian Relaxation based technique. But the wind power uncertainty was not considered in this work. The proposed approach was applied to a 36 unit test system and the results were compared with the other approaches.

Ummels et al (2007) have analyzed the impacts of wind power on thermal generation unit commitment and economic dispatch in the Dutch system, which has a significant share of combined heat and power units. A rolling commitment method was used to schedule the thermal units, where the ramping constraints and minimum on/off time constraints are considered. For a market environment, the true economic value of wind power and the costs
of variability and limited predictability of wind power have not been considered in this paper. Ongsakul & Nit (2008) have proposed a Fast Lagrangian Relaxation (FLR) method to minimize the consumer payment rather than the total supply cost. It was subjected to the power balance, spinning reserve, transmission and generator operating constraints. The FLR algorithm was improved by new initialization and adaptive adjustment of Lagrangian multipliers. But the ramp rate constraints were not included in this work.

1.4.2 Artificial Intelligence Approaches

The growing interest for researchers is the application of Artificial Intelligence (AI) approaches to solve UCP in deregulated environment. In the following section a survey of AI methods like Expert System (ES), Fuzzy Logic (FL), Artificial Neural Networks (ANN), Genetic Algorithm (GA), Evolutionary Programming (EP), Simulated Annealing (SA), Tabu Search (TS), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO) and Artificial Immune System (AIS) are presented.

1.4.2.1 Expert system

Mokhtari et al (1988) have proposed an expert system which combined the knowledge of the unit commitment programmer and an experienced operator. This expert system helped an inexperienced operator to a better unit schedule. The authors estimated that 300 rules were required to satisfy all operational requirements. Li et al (1993) have presented a graphical package expert system for unit commitment problem. The principle of this method was applied to more complicated cases with additional constraints.

Holttinen et al (2003) have adopted a simulation tool to determine the wind power impact on a thermal system operation. In this paper, a large
part of wind power integration challenges were effectively solved and investigated for Danish interconnected system.

1.4.2.2  Fuzzy logic method

Saneifard et al (1997) have developed a fuzzy logic system to solve the UCP. This method permitted a qualitative description of the behavior of a system, the system characteristics and its response, without need of exact mathematical formulations. A comparative results presented in this paper indicated that the use of fuzzy logic provided the outputs comparable to those of conventional dynamic programming. Also it claimed that this approach offered economical cost of operation. Yamin (2005) has implemented the fuzzy logic method to the Gencos UCP. This method presented an exact mathematical formulation for the behavior of the system and reported that the stochastic models have better performance than the deterministic model under uncertainty condition.

Liang & Liao (2007) have presented a fuzzy-optimization approach for solving the generation scheduling problem with the consideration of wind and solar energy systems. The goal of this method was to schedule unit’s power output and to minimize the total thermal fuel cost. Fuzzy set notations for the hourly load, wind speed, solar radiation, spinning reserve and total fuel costs were developed to obtain an optimal generation schedule under uncertain environment. The effectiveness of the proposed fuzzy-optimization approach was demonstrated through a simple system and the results revealed that the proposed approach was useful in reaching an optimal generation schedule when imprecision is considered. Siahkali & Vaikilian (2011) have implemented a type-2 fuzzy Membership Function (MF) to model the linguistic uncertainty of type-1 MF of available wind power generation. This paper exhibited how UC scheduling in an uncertain environment of type-1
fuzzy MF modeling can be performed using a single type-2 fuzzy MF when all type-1 MF were in the footprint of uncertainty of type-2 MF.

1.4.2.3 Artificial neural network

Sasaki et al (1992) have explored the feasibility of using Hopfield neural network to solve the UCP in which a large number of inequality constraints were handled. Once the states of generating units were determined, their outputs were adjusted according to the priority order. The proposed neural network determined an UC schedule of 30 units over 24 hour time periods. Gibescu et al (2006) have developed the wind speed time series interpolation for simulating wind power production at planned wind park locations, such that the spatial correlation between the sites is taken into account. The approach was tested with a small wind park having 10 generators with different wind power availability scenarios and generation. If the wind speed was forecasted to several hours in advance, then the generating schedule can efficiently accommodate the wind power generation. Delarue et al (2010) have investigated the profits of PBUC using an Artificial Neural Network model. The proposed technique was particularly effective only if proper values were assigned to the probabilities of the price scenarios. The probabilities of the price scenarios were selected based on the variation of power price in the market.

1.4.2.4 Genetic algorithm

Dasgupta & McGregor (1993) have presented a genetic approach for determining the priority order in the commitment of thermal units in power generation. The author examined the feasibility of using genetic algorithms and reported the simulation results in near optimal commitment of thermal units. The genetic-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. Kazarlis et al (1996) have implemented Genetic Algorithm to solve the UCP and the coding was executed in binary form. By the method of varying quality function, GA manages to locate the exact global solution at the end. A nonlinear transformation was implemented for fitness scaling in addition to the new operators of swap-mutation and swap-window hill-climb.

Richter & Sheble (2000) have proposed a PBUC formulation using Genetic Algorithm (GA) which allocated the fixed and transitional costs to the scheduled hours. In this paper many user friendly I/O routines were added to load the input data and to export the results. The UC-GA technique provided additional information to the users such that which of the schedules allow the user more market flexibility for a given level of profit. This work has not considered the wind power generation in PBUC formulation. Swarup & Yamashiro (2002) have employed the GA approach to the solution of UCP. This method was used for representing the chromosomes and encoding the problem search space for large-scale UC system. The proposed mechanism of chromosome, repair the UC schedule to satisfy the unit and system constraints.

Tuohy et al (2009) have examined the effects of stochastic wind and load on the UC and ED of power systems with high levels of wind power using the wilmar model. The model is built on the assumptions based on the hour-ahead or day-ahead system scheduling. The effectiveness of the method was examined and compared by analyzing the operational impact in the real-time market. Azadeh et al (2012) have presented a new GA approach for bidding strategy in a day-ahead market from the viewpoint of a generation company, in order to maximize their own profit as a participant in the market. Two approaches were considered based on bidding function and profit function: (i) as a supplier wishing to maximize the profit without considering
bidding function and (ii) as a supplier wishing to maximize the profit considering bidding function. The proposed algorithm provided only the average fitness value of profit in each iteration.

### 1.4.2.5 Evolutionary programming

Juste et al (1999) have proposed an algorithm that uses the Evolutionary Programming technique to solve the UCP, in which the initial population was generated randomly and then the solutions were evolved through selection, competition and random changes.

Chen & Wang (2002) have presented a cooperative co-evolutionary algorithm for UCP. The proposed algorithm was an extension of the traditional EP which has considerable potential for formulating and solving more complex problems by explicitly modeling the co-evolution of cooperating spices. Juste et al (2002) have considered a new PBUC in power and reserve generating markets. In this approach, the reserve probability of spinning reserve was assumed to be constant through-out the day in day-ahead markets. However, in competitive markets, the probability associated with spinning and non-spinning reserves was variable due to the volatile market prices.

Bouffard & Galiana (2008) have developed a stochastic unit commitment model to integrate significant wind power generation while maintaining the security of the system. Rather than being pre-defined, the reserve requirements were determined by simulating the wind power realization in the scenarios.
1.4.2.6 Simulated annealing

Mantawy et al (1998) have presented a Simulated Annealing (SA) algorithm and proposed new rules for randomly generating initial feasible UC schedules. SA used to solve the combinatorial optimization sub problem and the quadratic programming used to solve the ED sub-problem. Numerical results indicated the improvement in total production cost. Simopoulos et al (2008) have developed a new enhanced Simulated Annealing combined with dynamic ED method. In this paper, SA was used for scheduling the generators and the dynamic ED method was used to incorporate the ramp rate constraints in the UCP.

1.4.2.7 Tabu search

Mantawy et al (1998) have presented an approach based on Tabu Search (TS) method. Initial feasible UC schedules were generated randomly using newly proposed rules. TS was used to solve the combinatorial optimization sub-problem and the quadratic programming was used to solve the ED sub-problem. Numerical results specified an improvement in the quality of solution. Victoire & Jeyakumar (2005) have proposed an application of sequential quadratic programming technique for guiding the Tabu search. TS method was used for generating initial feasible UC schedules in this work. The UC scheduling problem was solved using a random-perturbation scheme.

Wang et al (2008) have proposed a security constrained UC algorithm that has taken into account the intermittency and variability of wind power generation. The uncertainty in wind power output was captured in a number of scenarios. Scenario reduction and variance reduction methods were applied to generate the scenarios. The algorithm was designed in a
conservative way that it does not allow for load curtailment in any scenario. The method can be improved by better modeling of wind forecasting errors.

1.4.2.8 Ant colony optimization

Saber & Alshareef (2008) have proposed a memory-bounded Ant Colony Optimization (ACO) approach which was inspired by the behaviors of real ant colonies and was a new cooperative agent’s approach based on parallel search. In the proposed approach, a set of cooperating agents called ‘ants’ are used to find optimal unit schedules for generating units and solved the computer memory requirements. Columbus et al (2012) have introduced a nodal ACO technique to solve PBUC problem. An optimal combination of binary nodes for unit ON/OFF status was available in the search space. It was represented to maintain good exploration and exploitation search capabilities for the movement of ants. The proposed model helped the Gencos to make decision on the quantity of power and reserve such that scheduling of generators received the maximum profit. The effectiveness of the proposed technique for PBUC problem was validated on 10 and 36 generating unit systems.

1.4.2.9 Particle swarm optimization

Zhao et al (2006) have presented an improved Particle Swarm Optimization (PSO) algorithm for solving UCP. This method utilized the particles information to control the process of mutation operation. In this paper, new rules were also proposed for proper selection of parameters. Yuan et al (2009) have proposed an improved binary PSO to solve the UCP. In this paper, the standard PSO was modified using the priority list and heuristic search methods to satisfy the Minimum Up Time (MUT) and Minimum Down Time (MDT) constraints. Though the proposed approach was superior
in terms of lesser total production cost but it produced the optimal schedule with large computational time.

Siahkali & Vakilian (2009) have presented a new approach for solving the generation scheduling problems based on PSO algorithm. The solutions of this problem satisfy the system constraints using a position adjustment strategy. The equality constraint was resolved by the principle of ‘sharing method’ which was used to provide a sharing mechanism between the thermal generating units. Jacob et al (2010) have implemented the PSO technique to maximize the profit of a generation company in deregulated power and reserve markets. The proposed algorithm found the economical scheduling plan for Gencos by considering both power and reserve generation. The effectiveness of the PSO method has been demonstrated and validated on the IEEE 30-bus system with six generator units as an individual Genco. Aghaei et al (2013) have applied the PSO algorithm to solve the multi-objective dynamic economic emission dispatch problem with the integration of wind power generation.

1.4.2.10 Artificial immune system

Huang (1999) has introduced the Immune Algorithm (IA) to solve the traditional unit commitment problem. IA is a basic defense system against bacteria, viruses, and other disease-causing organisms. It has dramatic and complex mechanisms that recombine the genes to cope up with the invading antigens, reducing the number of antibodies and excluding the antigens. Using this mechanism, the IA provided good performance as an optimization algorithm. Li et al (2006) have employed the strategy of IA technique for the UCP. With the embodiment of affinity computation, the possibility of stagnation in the iteration process was decreased and the computational performance was improved.
Liao (2006) has developed an improved IA for solving short term thermal generation scheduling problem. The proposed IA algorithm imitates the immune system to solve the multi-model function optimization problem. It has the capability to obtain feasible schedules with lesser convergence time. Rahman et al (2006) have presented an Artificial Immune System (AIS) based optimization technique for solving the economic dispatch problem in a power system. The proposed technique was implemented in the Clonal Selection algorithm with several cloning, mutation and selection parameters. The parameters were tested and compared in order to produce the best strategy such as cost minimization and least execution time. But this work has not considered the PBUC problem in deregulated environment. No researchers have applied the AIS approach to integrate the wind power generation in thermal PBUC problem.

1.4.3 Hybrid Approaches

Hybrid approaches are also used to solve many difficult engineering problems. The aim of the hybrid methods is to improve the performance of single approaches and to reduce the search space in large-scale optimization problems. The hybridization of two or more methods is mainly to speed up the convergence and to get better quality of solution compared with single approaches. A brief review of different hybrid approaches which have been reported in the literature is presented in this section.

Su & Hsu (1991) have developed a hybrid technique using fuzzy-dynamic programming to solve the UCP of Taiwan power. The membership functions were derived for the load demand, total cost and the spinning reserve using fuzzy set notations. With these membership functions, a recursive algorithm for fuzzy dynamic programming was used to determine the errors in the forecasted load demand. Cheng et al (2000) have presented a
hybrid approach of Lagrangian Relaxation and Genetic Algorithms (LR-GA) method to solve the UCP. The proposed approach incorporated GA into LR method to update the Lagrangian multipliers and produced better convergence.

Padhy (2001) has developed a hybrid model for solving the UCP with the help of AI based concepts of expert system, fuzzy modeling and neural network. In this paper, the fuzzy decision system was coupled with GA to the UC models independently. Attaviriyanupap et al (2003) have introduced a hybrid method between LR and EP for solving the PBUC problem. This hybrid technique was developed in such a way that EP has been used to update the Lagrangian multipliers in the traditional LR method. This paper has not considered the ramp rate limits of thermal generating units. Venkatesh et al (2003) have proposed various Evolutionary Programming techniques to the combined economic emission dispatch with line flow constraints and compared the results of each method. Yamin & Shahidehpour (2004) have presented a hybrid model between LR and GA to solve the PBUC problem in deregulated electricity markets. Here GA was used to update the Lagrangian multipliers and the optimal bidding curves as a function of generation schedule were also derived. This paper has not included the wind power generation in the scheduling process.

Coello & Cortes (2004) have proposed an algorithm based on a hybrid model of the Immune Algorithm and GA to handle the constraints of all types used for global optimization. The proposed approach was highly competitive with respect to constraint-handling techniques which are considerably more complex to implement. Rajan & Mohan (2007) have proposed the hybrid EP based Simulated Annealing method to solve the short-term UCP. In this work, the offspring obtained from the EP algorithm was
given as input to SA and the SA was used to obtain the refined unit status by avoiding entrapment in local minima.

Kannan et al (2007) have proposed metaheuristic techniques and hybrid approach for generation expansion planning in partially deregulated environment. In this model, the utility maximizes its profit and ensures profits for all the participating IPPs. Among the different techniques, the hybrid approach performed better than any other techniques. Li et al (2009) have established a mathematical model of UCP for analyzing the generating units in modern power plants using an Immune-Tabu Search hybrid algorithm. Each feasible individual solution in the IA method was used as an initial solution to the TS algorithm after certain iterations of IA. The proposed hybrid method was tested to 10, 20, 40 and 80 units thermal system for a period of 24 hours. Pappala et al (2009) have presented a stochastic model for optimal scheduling of the generators in a wind integrated power system. This model considered the demand and wind power generation uncertainties in the system. A PSO based scenario generation and reduction algorithm was used for modeling the uncertainties. The stochastic UCP model was solved using a self adaptive PSO algorithm.

Siahkali & Vakilian (2010) have developed a solution method for generation scheduling of power system. It was taken into account the stochastic behavior of the load magnitude and the wind power generation. The proposed approach was used to make a decision on fixed state of units operation in different scenarios. The results of all scenarios have been studied for a 12-unit test system. Sturt & Strbac (2012) have proposed a stochastic UCP using scenario tree generation methodology for high wind power penetrations. The UC scheduling simulations with rolling planning were compared with different tree topologies and scenario generation methods.
From the literature, it has been observed that the major limitations with the existing methods are complexity of search space due to problem dimensions, generation of infeasible solutions, constraints handling, large computational time and integration of wind power generation in unit commitment. Therefore, there is a need for up-gradation of the existing methods or development of new models for obtaining an optimal solution for the PBUC problem. Hence, this research has been paying attention on, efficient, near-optimal and less computational time requirements scheduling algorithms, which can be applied to large-scale power systems. Compared to other conventional methods, Lagrange Relaxation approach is more flexible for handling different types of operating constraints in a power system. The duality of LR method provides decomposition solution to the large-scale UCP and hence computationally simple to incorporate various constraints. The Genetic Algorithm represents each variable in PBUC problem as a binary number of bits. Hence GA is able to find multiple good PBUC schedules in a reasonable amount of time. The AIS method is able to explore the solution space in obtaining the global optimum solution with faster convergence rate. AIS retain the optimal and near optimal antibodies through iterations to achieve a higher-quality feasible solution. Also, the thermal PBUC and wind-thermal PBUC problem is commonly termed as Gencos PBUC problem in this thesis.

1.5 OBJECTIVES OF RESEARCH WORK

The objectives of this research work are outlined below:

- To maximize the profit of electric power Generation company and minimize the thermal operating cost with the integration of wind power generation.
To develop a mathematical model for thermal PBUC and wind-thermal PBUC problem with the inclusion of system constraints, thermal and wind generator constraints.

To investigate the performance of LR method to the Gencos PBUC problem for different case studies.

To implement the GA technique to the Gencos PBUC problem for analyzing the suitability of this approach.

To implement and investigate the performance of an Artificial Immune System approach to the Gencos PBUC problem.

To design AIS based GA as hybrid approach and analyze its performance as applied to the Gencos PBUC problem for different case studies.

The flow diagram of this research work is shown in Figure 1.7, where the research focus includes three sections: (i) Mathematical formulation of thermal PBUC and wind-thermal PBUC problem (ii) Objective of the Gencos PBUC problem and (iii) Implementing the conventional LR method, GA approach, AIS algorithm and hybrid (AIS-GA) approaches to achieve the objective of the Gencos PBUC problem.
1.6 ORGANIZATION OF THESIS

This thesis consists of seven chapters and has been organized as follows:

The first chapter of this thesis intends to present a brief introduction about the power system deregulation and unit commitment problem in deregulated power systems. It also provides a survey of literature concerning the features of existing methods used to solve the profit based unit commitment problem.

Chapter 2 deals with the mathematical formulation of thermal PBUC problem and wind-thermal PBUC problem along with system constraints, thermal and wind generator constraints.
Chapter 3 investigates the performance of Lagrange Relaxation (LR) method to search the optimal PBUC schedule for different case studies based on the Lagrange multipliers.

Chapter 4 discusses the solution approach to Gencos PBUC problem using Genetic Algorithm along with the theoretical principles of GA and essential features of the algorithm. Also, presents the simulation results of PBUC on different case studies using GA.

Chapter 5 focuses on the performance of Artificial Immune System for solving thermal and wind-thermal PBUC problem with different case studies. The key features of immune system principles and mechanisms that inspire the developments of AIS are also discussed in this chapter.

Chapter 6 proposes the hybrid AIS-GA algorithm to solve Gencos PBUC problem for different case studies. In addition, the results are compared with the other methods for validating the superiority of hybrid algorithm.

Chapter 7 gives the summary of research findings and scope for future research work in Gencos PBUC problem.