OPTIMAL SHORT-TERM THERMAL UNIT COMMITMENT USING FUZZY LOGIC

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

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in
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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **"Optimal Short Term Thermal Unit Commitment Using Fuzzy Logic"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of *Mr. Parag Nijhawan, Sr.Lecturer, EIED.*

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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

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Maninder Kaur

ABSTRACT

Economic dispatch and Unit Commitment are widely used for the real time operation of power system. The effectiveness of economic dispatch is well understood when the objective is to schedule the committed generators to meet the load, maintain voltages and frequency within prescribed tolerances and minimize operating cost without unduly stressing the equipment. An approach for solving the unit commitment problem using fuzzy logic has been proposed in this thesis. It is demonstrated through numerical problem that a fuzzy logic based approach achieves a logical and feasible economical cost of operation of the power system. The solution of the problem is also obtained using Dynamic Programming. A set of linguistic fuzzy control rules are developed to establish the relationship between the inputs and the output. The fuzzy variables associated with the unit commitment are Load demand, Incremental cost, Start up cost and Power generation. The approach has been applied to a system comprised of 3 generating units. A MATLAB code has been developed for solving fuzzy logic based unit commitment problem. Results indicating comparison of the cost solutions using the fuzzy logic and the conventional Dynamic Programming are also presented in this work.

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CHAPTER 1
INTRODUCTION

1.1 OVERVIEW

The aim of the proposed work is to find the generation scheduling such that the total operating cost can be minimized subjected to variety of constraints using Dynamic programming and fuzzy logic. A set of linguistic fuzzy control rules are developed to establish the relationship between the inputs and the output. The total cost includes both fuel cost and start up cost. Comparison of results obtained from Dynamic Programming and fuzzy logic are shown.

1.2 LITERATURE REVIEW

The size of electric power system is increasing rapidly to meet the energy requirements. A number of power plants are connected in parallel to supply the system load by interconnection of power stations. With the development of integrated power systems (that is grid systems) it becomes necessary to operate the plant units most economically. [20] “Economic dispatch” has a common, general meaning- the practice of operating a coordinated system so that the lowest-cost generators are used as much as possible to meet demand, with more expensive generators brought into production as load increases. [30]

According to EPAct’s definition of economic dispatch -“the operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognizing any operational limits of generation and transmission facilities”.[31] Kothari & Dhillon defines economic dispatch as that which minimizes the total operating cost of a power system while meeting the total load plus transmission losses within generator limits.[11] Sakorn Panta & Suttichai Premrudeepchacharn defines the economic dispatch as a computational process where the total required generation is distributed among the generation units in operation, by minimizing the selected cost criterion, subjected to load and operational constraints [22] .

Electricity loads vary over time, rising and falling in daily and weekly patterns. Because electricity travel at the speed of light and cannot be stored inexpensively, generation must be available that can follow changes in load almost instantaneously. However, generators vary widely in their costs and capability; fossil fired units with low marginal costs tend to be relatively inflexible, and generators that can follow load tend to be more expensive. Generators are also subject to fuel limitations and environmental regulations that restrict their availability. The reliability consideration demands that excess generation be available in reserve, along with transmission capacity, to respond to sudden, unplanned contingencies. Many factors influence economic dispatch in practice. These include regulatory, environmental, scheduling, unit commitment and reliability practices. Economic dispatch is best thought of as a constrained cost minimization process because it maintains a balance between economic efficiency, reliability and other factors etc [2]. The characteristics of power system lead to a natural sequencing in system operations- first, determine which units should be turned on and made available to serve loads (called unit commitment) and, second, determine how much production to call from each resource (economic dispatch).

Unit commitment refers to the strategic choice to be made in order to determine which of the available power plants should be considered to supply electricity. Unit commitment is not the same as dispatching. Dispatching consists of fitting a given set of power plants into a certain electric demand whereas Unit commitment appoints the set of plants from which dispatching can choose. Unit commitment choose plants taking into account a wide variety of parameters, technological aspects (such as minimal operating point, minimum up and down time and transient behavior) as well as economical considerations (such as start- up cost and operational costs) and social elements (such as availability of staff and work- schemes).Unit commitment enables utilities to minimize electricity generation costs [6, 29].

Unit commitment and economic dispatch when combined together is a useful tool to find the most economical generation schedule with which demand and spinning reserve requirement are supplied and all generating unit constraints, such as unit minimum and maximum generation capabilities and unit minimum up and down time over a time horizon. Many methods have been developed to tackle unit commitment economic optimization like priority list, lagrangian relaxation and dynamic programming [35, 37].

In our work, dynamic programming method is used. Dynamic programming (DP) is name used for methods in which a- priori impossible or improbable possibilities are left out [25,33]. Lowery [21] starts from a previously determined optimal unit commitment planning and gradually adds power plants to obtain optimal solutions for higher demand. Cohen and Yoshimura [9] propose a branch-and-bound model (or "tree" concept) which also starts from a previously obtained optimum. Van den Bosch and Hondred [32] decompose the main problem into several sub-problems that are easier to solve. The decomposition proposed by Synder et al. [34] consists of grouping power plants from the same type. In order to take into account uncertainties (e.g. uncertain electricity demand), Su and Hsu [28] combined DP with fuzzy logic.

Fuzzy logic was discovered in 1965 by Lotfi Zadeh at the University of California, Barkeley [13]. The use of fuzzy logic has received a lot of attention in recent years because of its usefulness in reducing the need for complex mathematical models in problem solving. Rather, fuzzy logic employs linguistic terms, which deal with the casual relationship between input and output variables. For this reason, fuzzy logic approach makes it easier to manipulate and solve many problems, particularly where the mathematical model is not explicitily known, or is difficult to solve. Furthermore, fuzzy logic is a technique, which approximates reasoning, while allowing decisions to be made efficiently [5, 8, 36]. In our work, to reach an optimal Unit Commitment schedule, generation cost and load demand are all expressed in fuzzy set notation.

The primary objective of our demonstration has been that, if the process of unit commitment can be described linguistically then such linguistic descriptions can be translated to a solution that yields similar results compared to dynamic programming. In fact, the computational burden may be the same or more; however, the qualitative interpretation of results using fuzzy logic appears to be attractive [26].

The security of a power system is measured by the ability of the system to withstand contingency cases without violating normal operating conditions. The principal task of an electric power system is to deliver the electric power requested by the customers, without exceeding acceptable voltage and frequency limits. This task has to be performed in real time in a safe, reliable and economical manner. There are two types of security assessments: static security assessment and dynamic security assessment[7, 16]. In both types different operational states are defined as follows:

1. Normal or Security State: In the normal state, the demands of the customer are met and operating limit is within prescribed limits.
2. Alert or Critical State: In this state, the system variables are remaining in limits and constraints are also satisfied, but even a little disturbance can lead to variation towards instability.
3. Emergency or Unsecure State: If the security related inequality constraints are violated, then the power system enters the emergency mode of operation.

1.3 OBJECTIVE

Economic dispatch and Unit Commitment are widely used for the real time operation of power system. The effectiveness of economic dispatch is well understood when the objective is to schedule the committed generators to meet the load, maintain voltages and frequency within prescribed tolerances and minimize operating cost without unduly stressing the equipment. The objective of the proposed work is to commit the units with the conventional method (Dynamic Programming) and with the AI technique (Fuzzy logic) without violating the constraints and to compare the results in order to find the best suitable method. The proposed work includes formulation and coding in MATLAB.

1.4 ORGANIZATION OF THESIS

The thesis includes 6 chapters altogether. The chapters are organized as follows:

Chapter 1

Chapter introduces the overview i.e. brief outline of problem, literature survey of the related topics of the problem. This chapter also includes the objective of the thesis.

Chapter 2

This chapter is devoted to economic dispatch of the thermal power systems. This section includes the brief introduction of the economic dispatch; optimal generation scheduling i.e. how the problem is mathematically defined with the equality and inequality constraints. It also explains the benefits and current practices for optimizing dispatch.

Chapter 3

Chapter provides an introduction to the unit commitment, various constraints included in unit commitment. It also explains that how to compute the fuel cost. Various conventional methods of the unit commitment are explained. And lastly, the comparison between the economic dispatch and unit commitment is also explained.

Chapter 4

Chapter provides an introduction to fuzzy logic. It also provides the necessary background of the fuzzy logic. It explains that what fuzzy offers and what does it means. Basics of fuzzy such as fuzzy sets, fuzzy set operations, fuzzy rules and fuzzy controls are discussed in this chapter. The step-wise procedure to solve the unit commitment using fuzzy logic is also presented. Fuzzy UCP model is presented and how to implement the fuzzy sets and fuzzy rules to the unit commitment problem is also presented. Defuzzification process is also discussed.

Chapter 5

This chapter deals with problem formulation of the topic. The step-wise procedure to solve the unit commitment problem is presented. It includes the fuel cost, start-up cost and transmission losses calculations. An efficient algorithm and flowchart of unit commitment are also shown. And lastly, the fuzzy dynamic algorithm and flowchart are also provided.

Chapter 6

This chapter concludes this thesis work purely on the grounds of the results obtained.

CHAPTER 2
ECONOMIC DISPATCH

2.1 INTRODUCTION

The main aim of electric supply utility has been identified as to provide the smooth electrical energy to the consumers. While doing so, it should be ensured that the electrical power is generated with minimum cost. Hence in order to achieve an economic operation of the system, the total demand must be appropriately shared among the units. This will minimize the total generation cost for the system with the voltage level maintained at the safe operating limits. Thereby, fulfilling the main objective [3].

Economic dispatch is defined as the process of allocating generation levels to the generating units in the mix so that the system load is fully supplied in the most economic way.[4] The method of economic dispatch for generating units at different loads must have total fuel cost at the minimum point. There are many conventional methods that are in use to solve economic dispatch problem such as Lagrange multiplier method, Lambda iteration method and Newton Raphson method. In the conventional methods, it is difficult to solve the optimal economic problem if the load is changed. It needs to compute the economic dispatch each time which uses a long time in each of computation loops [15, 22].

It is a computational process where the total required generation is distributed among the generation units in operation, by minimizing the selected cost criterion, and subjects it to load and operational constraints as well. Most programs use economic dispatch in real- time energy management power system control to allocate the total generation among the available units, unit commitment and in some other operation functions [17, 20] .

2.2 GENERATOR OPERATING COST

The total cost of operation includes the fuel cost, cost of labour, supplies and maintenance. Generally, costs of labour, supplies and maintenance are fixed percentages of incoming fuel costs. The power output of fossil plants is increased sequentially by opening a set of valves to its steam turbine at the inlet. The throttling losses are large when a valve is just opened and small when it is fully opened.

As a result, the operating cost of a plant has the form shown in Fig 2.2.2. For dispatching purposes; this cost is usually approximated by one or more quadratic segments. So, the fuel cost curve in the active power generation, takes up a quadratic form, given as

$$F(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i Rs/hr \quad \ldots(2.1)$$

The fuel cost curve may have a number of discontinuities. The discontinuities occur when the output power is extended by using additional boilers, steam condensers, or other equipment. They may also appear if the cost represents the operation of an entire power station, and hence cost has discontinuities on paralleling of generators. Within the continuity range the incremental fuel cost may be expressed by a number of short line segments or piece-wise linearization [1, 11].

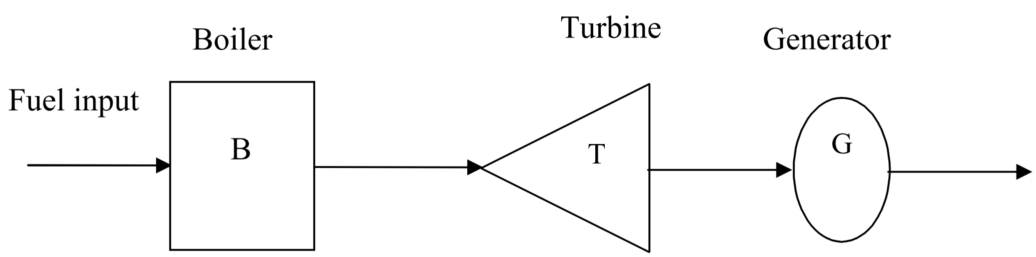


Figure 2.1: Simple model of a fossil plant

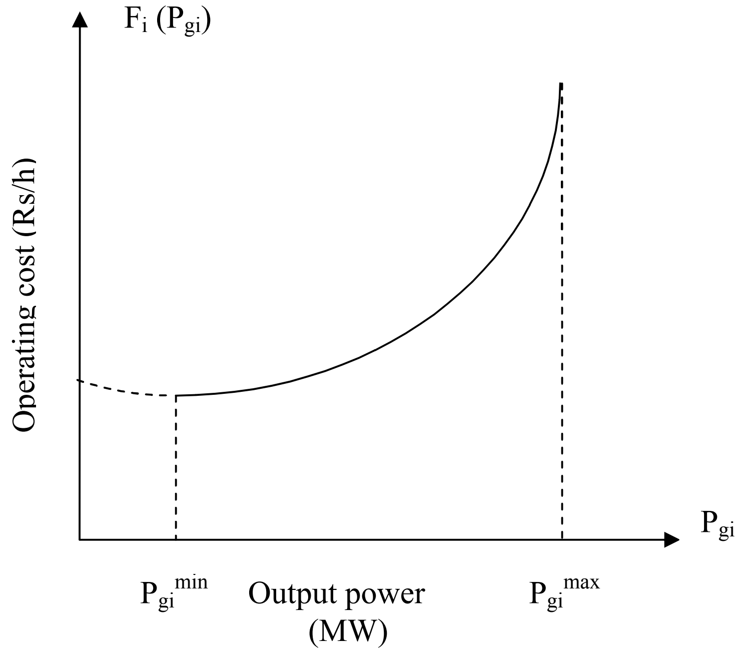


Figure 2.2: Operating costs of a fossil fired generator. P_{gi}^{min} and P_{gi}^{max} are the lower and upper limits on its output.

The P_{gi}^{min} is the minimum loading limit below which, operating the unit proves to be uneconomical (or may be technically infeasible) and P_{gi}^{max} is the maximum output limit.

2.3 OPTIMAL GENERATION SCHEDULING

The economic dispatch problem is defined as the one that minimizes the total operating cost of a power system while meeting the total load plus transmission losses within generator limits. When long distance transmission of power is involved, the transmission losses cannot be ignored. If the transmission losses are neglected, then the total system load can be optimally divided among the various generating plants using the equal incremental cost criterion. A modern electric utility is capable of serving a vast area of relatively low load density [11]. The transmission losses may vary from 5 to 15 per cent of the total load. It is essential to keep an account for transmission losses while developing an economic load dispatch policy. Mathematically, the problem is defined as

Minimize $$F(P_{gi}) = \sum_{i=1}^{NG} (a_i P_{gi}^2 + b_i P_{gi} + c_i) Rs/hr \qquad \ldots(2.2)$$

Subject to

i. the energy balance equation

$$\sum_{i=1}^{NG} P_{gi} = P_D + P_L \qquad \ldots(2.3)$$

ii. and the inequality constraints

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \qquad \ldots(2.4)$$

where

a_i, b_i and c_i are the cost coefficients

P_D is the load demand

P_{gi} is the real power generation and will act as decision variable

NG is the number of generation buses

P_L is the transmission power loss

B-coefficients are used to express transmission losses as a function of generator powers. Under normal operating conditions, the transmission losses are found to be quadratic in the injected bus real powers. The general form of the loss formulae using B-coefficients is

$$P_L = \sum_{i=1}^{NG} \sum_{j=1}^{NG} P_{gi} B_{ij} P_{gj} \qquad \ldots(2.5)$$

where

P_{gi} and P_{gj} are the real power injections at the *i*th and *j*th buses

B_{ij} are the loss coefficients which are constant under certain assumed conditions

NG is the number of generation buses

The constrained optimization problem can be converted into an unconstrained optimization problem by using Lagrange multiplier method. It is used where the function is minimized (or maximized), satisfying the side conditions in the form of equality constraints. Using Lagrange multipliers, an augmented function is defined as

$$L(P_{gi},\lambda) = F(P_{gi}) + \lambda\left(P_D + P_L - \sum_{i=1}^{NG} P_{gi}\right) \quad \ldots(2.6)$$

where

λ is the Lagrangian multiplier

The incremental cost can be obtained as

$$\left(\frac{\partial F(P_{gi})}{\partial P_{gi}}\right) L_i = \lambda \quad \ldots(2.7)$$

where

$$L_i = \frac{1}{1 - \dfrac{\partial P_L}{\partial P_{gi}}} \quad \ldots(2.8)$$

L_i is called the penalty factor of the *i*th plant.

The value of P_{gi} can be obtained as

$$P_{gi} = \frac{\lambda\left(1 - B_{i0} - \sum_{j=1}^{NG} 2B_{ij}P_{gj}\right) - b_i}{2\left(a_i + \lambda B_{ii}\right)} \quad \ldots(2.9)$$

Without transmission losses

The value of P_{gi} can be obtained as

$$P_{gi} = \frac{\lambda - b_i}{2a_i} \quad \ldots(2.10)$$

The incremental cost can be obtained as

$$\lambda = \frac{P_D + \sum_{i=1}^{NG} \dfrac{b_i}{2a_i}}{\sum_{i=1}^{NG} \dfrac{1}{2a_i}} \quad \ldots(2.11)$$

2.4 BENEFITS OF ECONOMIC DISPATCH

- If the geographic scope and electrical diversity of the area taken under unified dispatch increases, then economic benefits also tend to increase.
- Retail customers benefit if cost savings are passed through in retail rates.

- Economic dispatch reduces fuel consumption and emissions as high-efficiency units frequently displace lower-efficiency units using the same or similar fuel.

Economic dispatch requires well maintained balance between economic efficiency, reliability, and various other factors, such as the ability of a given generating unit to shift output at short notice, and scheduling limitations imposed by environmental laws, hydrological conditions, and fuel characteristics. It means that the economic dispatch is "constrained cost minimization process" [2, 6, 7, 10].

2.5 CURRENT PRACTICES FOR OPTIMIZING DISPATCH

1. Coal-fired generation resources are normally dispatched as simple options with the dispatch cost consisting of the fuel cost, environmental cost and variable operating and maintenance costs. In addition, many of these resources are occasionally used to supply operating reserves as well (contingency and regulating) for the control areas.
2. Natural-gas-fired generation is normally dispatched as a spark spread option without long-term fuel contracts and includes variable operating, maintenance, and start-up costs. The decision of natural gas and electricity purchase is made in the day-ahead market and again in the hour-ahead market.
3. Hydro generation resources, with storage capability, are normally dispatched as swing options based on the opportunity cost of dispatching in some other time period.
4. Contractual resources are dispatched either as simple, spark spread, wing, or compound options, depending on the terms of the agreements [29, 30, 31].

CHAPTER 3
UNIT COMMITMENT

3.1 INTRODUCTION

The aim of economic scheduling of generator is to guarantee the optimum combination of generators connected to the system to supply the load demand. The economic dispatch problem involves two separate steps namely 'unit commitment' and 'on-line economic dispatch'. The unit commitment involves the selection of units that will supply the anticipated load of the system at minimum cost over a required period of time as well as provide a specified margin of the operating reserve, known as the spinning reserve. The on-line Economic dispatch distributes the load among those operating units that are paralleled with the system in such a manner so as to minimize the total cost of supplying the minute to minute requirements of the system.

Total running cost is the main factor that controls the most desirable load allocation between various units. Fuel cost makes the major contribution to operating cost of thermal plants. Fuel supplies for the thermal plants can be coal, natural gas, or nuclear fuel. The other costs such as cost of labour, supplies, maintenance etc being difficult to determine and approximate are assumed to vary as a fixed percentage of fuel cost. Therefore these costs are included in the fuel cost and are given as a function of generation. This function is defined as a nonlinear function of plant generation.

The main objective of this thesis is to find the generators of different units for optimal generation of thermal system so that the total fuel cost is minimum, subjected to satisfying certain constraints. Basically there are two types of constraints, namely, equality constraints and inequality constraints [20].

Like the human activities follow cycles, similarly most systems supplying services to a large population experience cycles. This includes transportation systems, communication systems, as well as electric power systems. In the case of an electric power, the total load on the system will generally be higher during the day time and early evening when industrial loads are high, lights are on, and so forth, and lower during the late night and early morning when most of the population is asleep. In addition, the use of electric power has a weekly cycle, the load being lower during the weekend days than week days. To “commit” a generating unit is to “turn it on;” that is, to bring the unit to the desired speed, synchronize it to the system, and connect it so that it can deliver power to the network. The problem with “commit enough units and leave them on line” is one of economics [1].

3.2 CONSTRAINTS IN UNIT COMMITMENT

Many constraints can be applied on the unit commitment problem. Each individual power system, power pool, reliability council, et.al, may impose different rules on the scheduling of units, depending on the generation makeup, load-curve characteristics.

3.2.1 Spinning Reserve

Spinning reserve describes the total amount of generation available from all units synchronized (i.e. spinning) on the system, minus the present load supplied and losses being incurred. Spinning reserve must be carried out in such a way that the loss of one or more units does not cause too far a drop in system frequency.

Spinning reserve must obey certain rules which will specify that reserve must be capable of making up the loss of most heavily loaded unit in a given period of time. Reserve requirement also calculated as a function of the probability of not having sufficient generation to meet the load, by making people.

3.2.2 Thermal Unit Constraints

Thermal units usually require a crew to operate them, especially when turned on and turned off. A thermal unit can undergo only gradual temperature changes, which in turn translates into a time period of some hours that are required to bring the unit “on-line”. As a result of such restrictions various constraints arise, in the operation of a thermal plant, such as:

Minimum up time*:* once the unit is running, it can not be turned off immediately.

Minimum down time*:* once the unit is decommitted, there is a minimum time before it can be recommitted.

Crew constraints*:* if a plant consists of two or more units, they cannot both be turned on at the same time since there are not enough crew members to attend both units at the start up.

In addition, a certain amount of energy must be expended to bring the unit on-line as the temperature and pressure of the thermal unit are required to move slowly, This energy does not result in any MW generation from the unit and is brought into the unit commitment problem as a "start-up cost." [1].

The start-up cost can vary from a maximum "cold-start" value to a much smaller value, if the unit was only turned off recently and is still relatively close to operating temperature. There are two approaches for treating a thermal unit during its down period. The first approach allows the unit's boiler to cool down and then heat back, it upto the operating temperature, in time for a scheduled turn on. The second approach (called banking) requires that sufficient energy should be given to the boiler to just maintain operating temperature. The costs for the two are compared so that, if possible, the best approach (cooling or banking) can be chosen.

Start up cost when cooling is given by

$$C_c\left(1-\varepsilon^{-t/\alpha}\right)\times F + C_f \qquad \ldots(3.1)$$

where

C_c = cold-start cost (MBtu)

F = fuel cost

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

α = thermal time constant for the unit

t = time (h) the unit was cooled

Start-up cost when banking is given by

$$C_t \times t \times F + C_f \qquad \ldots(3.2)$$

Where

C_t = cost (MBtu / h) of maintaining unit at operating temperature

Up to a certain number of hours, the cost of banking will be less than the cost of cooling.

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

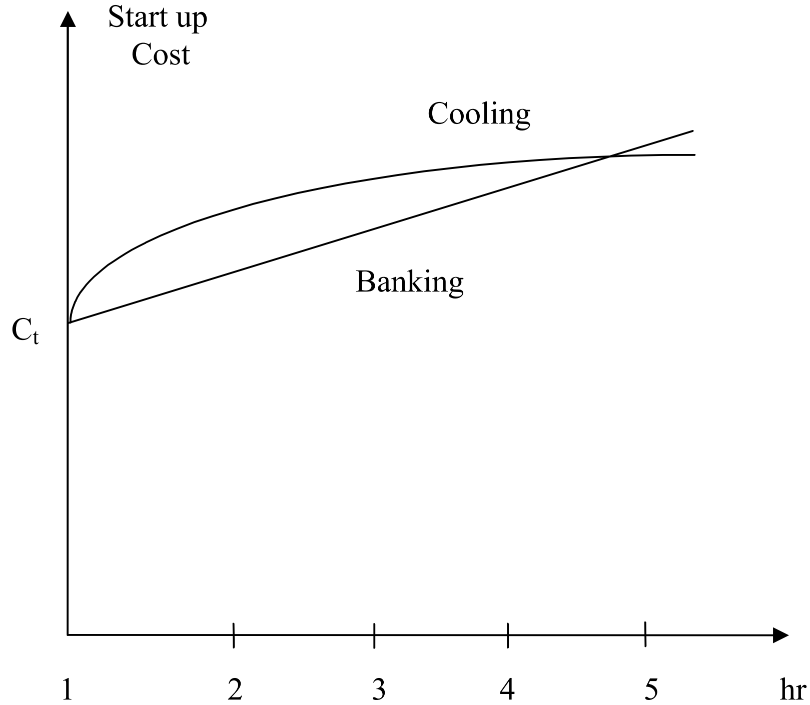


Fig 3.1: Time-dependent start-up costs.

3.2.3 Other constraints

3.2.3.1 Hydro-constraints

Unit commitment cannot be completely separated from the scheduling of hydro units whereas it can be assumed that the hydro thermal scheduling can be separated from the unit commitment problem. But we cannot assess that the result will be an optimal solution.

3.2.3.2 Must run

For voltage support on the transmission network or for such purposes as supply of steam for uses outside the steam plant itself, some units are given a must-run status during certain times of the year.

3.2.3.3 Fuel constraint

A system in which some units have limited fuel, or else have constraints that require them to burn a specified amount of fuel in a given time, presents a most challenging unit commitment problem [1, 3].

3.2.4 Fuel cost computation

Fuel cost in unit commitment problem may be divided into two categories: the transitional cost and production or generation cost. Generally the transitional cost is the cost associated with the starting of the unit and it may also include shut down cost. The production cost is the fuel cost required to meet the load. It depends on the unit loading, heat rate and fuel price. Computation of these costs is given below:

3.2.4.1 Transitional Cost

The shutting down of units are not associated with cost, normally but a provision can be made to include shutdown costs in the computation of total cost. A constant cost may be specified for each unit as the shut down cost. This cost is taken to be independent of the length of time; the unit has been running before the shutdown.

In the unit commitment problem usually some form of start up cost is considered. A simple practice is to assume a constant cost irrespective of the unit down time. However, in order to provide a more accurate measure of the actual cost involved, a time dependent start up cost is required. The start up cost is expected to be dependent on the temperature of the unit considered and hence on it's down time. Since the cooling rate of a unit is approximately exponential, an exponential start up cost curve is generally accepted though other forms of cost curve may also be used.

It will be more economical to keep the unit in hot standby instead of shutting it down completely. The choice between shutdown and hot standby will depend on the two cost curves and the length of time, a unit is kept out-of-service. Generally, a constant fuel rate is required to maintain the boiler temperature and pressure, and thus the standby cost curve may be assumed to be a linear function of the shutdown time. As a result of this, a unit will be allowed to cool or be in hot standby as determined by the lower of the startup and hot standby costs [6].

3.2.4.2 Production cost

The production cost is the cost of the fuel required by a given set of on-line generating units to meet the load demand in the system. Since the overall objective of the unit commitment problem is to minimize the overall total cost, hence the production cost should also get minimized as well. Numerous methods of economic dispatch are available to determine the minimal production cost. As compared to the number of economic dispatches that would be performed, a simple, feasible and fast economic dispatch procedure is used. The transmission losses are assumed to be a quadratic function of the total system generation.

The units are assumed to have piece wise linear generation cost curves and the loading is carried out beginning with the section having the lowest incremental cost. The dispatch continues by loading the section having the next lowest incremental cost and the process stops until the desired generation is met or no more sections can be dispatched.

The dispatching is carried out such that unit generations are always within their upper and lower limits. It is also taken care that the various spinning reserve requirements described above are not violated. A dispatch which satisfies all of the constraints is termed as a feasible one. Using the described method, an economic and feasible dispatch is always determined whenever one exists. Since each unit section is considered only once and no iteration is involved, the dispatch is fast. The units are considered once and in the order of prespecified priority in order to reduce the dispatching effort [34, 36] .

3.3 **UNIT COMMITMENT SOLUTION METHODS**

The unit commitment problem determines the combination of available generating units and schedules their respective outputs in order to satisfy the forecasted demand maintaining the minimum total production cost, under the operating constraints enforced on the system for a specified period that usually varies from 24 hrs to one week. Attempts to develop rigid unit operating schedules, for more than one week in advance, are extremely curtailed due to uncertainty in hourly load forecasts at lead time.

Apart from achieving minimum total production cost, generation schedules need to satisfy a number of operating constraints. These constraints reduce freedom in their choice of start up and shutting down generating units. The constraints to be satisfied are usually the status restriction of individual generating units, minimum up time, minimum down time, capacity limits, generation limits for the first and last hour, power balance constraint, spinning reserve constraint, hydro constraints, etc [27].

The high dimensionality and combinatorial nature of unit commitment problem failure made for the development of any rigorous mathematical optimization method, which is capable of solving any real-size system problem as a whole. The available approaches for solving unit commitment problem can usually be classified into *heuristic* *methods* and *mathematical programming methods.* In addition the proposed mathematical programming approaces are *dynamic programming and Langragian relaxation.*

These two approaches are most widely used to develop industry grade unit commitment programs. Their major advantage being the reasonable computation time required by them when compared to other approaches. The most talked about techniques for the solution of the unit commitment problem are:

- Priority-list schemes.
- Dynamic programming (DP)
- Lagrange relation (LR)

3.3.1 Priority-List Methods

This is the simplest unit commitment solution method. It consists of creating a priority list of units. The priority list can be obtained in a very simple manner by noting the full-load average production cost of each unit, where a full-load average production cost is defined as the net heat rate at full load, multiplied by the fuel cost.

3.3.2 Dynamic Programming Solution

Dynamic programming acts as an important optimization technique with broad application areas. It decomposes a problem into a series of smaller problems, solves them, and develops an optimal solution to the original problem step-by-step. The optimal solution is developed from the sub problem recursively. In its fundamental form, the dynamic programming algorithm for unit commitment problem examines every possible state in every interval. Some of these states are found to be infeasible and hence they are rejected instantly. But even, for an average size utility, a large number of feasible states will exist and the requirement of execution time will stretch the capability of even the largest computers. Hence many proposed techniques use only some part of simplification and approximation to the fundamental dynamic programming algorithm.

Dynamic programming has many advantages over the enumeration scheme. The chief advantage being the reduction in the dimensionality of the problem. Suppose we have found units in a system and any combination of them could serve the single load. A maximum of 2^N-1 combinations are available for testing.

The imposition of priority list, arranged in order of the full load average cost rate would result in a theoretically correct dispatch and commitment only if:

1. No load costs are zero.
2. Unit input-output characteristics are linear between zero output and full load.
3. There are no other restrictions.
4. Start-up costs have a fixed amount.

In the dynamic programming approach that follows, it is assumed that:

1. A state consists of an array of units with only specified units operating at a time and rest off-line.
2. The start-up cost of a unit is independent of the time it has been off-line (i.e., it is a fixed amount).
3. There are no costs for shutting down a unit.
4. There is a strict priority order, and in each interval a specified minimum amount of capacity must be operating.

A feasible state is one in which the committed units can be supply the required load and that meets the amount of capacity at each period [27, 33, 34].

3.3.2.1 Forward Dynamic Programming Approach

One could set up a dynamic-programming algorithm to run backward in time, starting from the final hour and studying it back to the initial hour. Conversely, one could set up the algorithm to run forward in time from the initial hour to the final hour. The forward approach has distinct advantages in solving the generator unit commitment problem. For example, if the start-up cost of a unit is a function of the time it has been off-line (i.e., its temperature), then a forward dynamic-program approach is more suitable, using this the previous history of the unit can be computed at each stage. There are other practical reasons for going forward. The initial conditions are easily specified and the computations can go forward in time as long as required.

3.3.3 Lagrange Relaxation Solution

The solution of the unit commitment problem using dynamic programming method has many disadvantages as far as large power systems with many generating units are concerned. This is so because of the necessity of forcing the dynamic programming solution to search over a small number of commitment states that must be tested in each time period in order to reduce the number of combinations [1, 22].

In the Lagrange relaxation technique these disadvantages disappear. The Lagrange Relaxation technique is based on a dual optimization approach. Its utilization in production unit commitment problem is much more recent than the dynamic programming methods.

Defining the variable U_i^t as

$U_i^t = 0$ if unit i is off-line during period t

$U_i^t = 1$ if unit i is on-line during period t

Several constraints and the objective function of the unit commitment problem are defined as:

1. Loading constraints:

$$P_{load}^t - \sum_{i=1}^{N} P_i^t U_i^t = 0 \quad \text{for } t = 1.....T \qquad \ldots(3.3)$$

2. Unit limits:

$$U_i^t P_i^{\min} \le P_i^t \le U_i^t P_i^{\max} \quad \text{for } \; i = 1.....N \quad \text{and} \quad t = 1.....T \qquad \ldots(3.4)$$

3. Unit minimum up and down time constraints.
4. The objective function is:

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\left[F_i\left(P_i^t\right) + startup\cos t_{i,t}\right]U_i^t = F\left(P_i^t, U_i^t\right) \qquad \ldots(3.5)$$

The Lagrange function obtained:

$$L\left(P,U,\lambda\right) = F\left(P_i^t, U_i^t\right) + \sum_{t=1}^{T}\lambda^t\left(P_{load}^t - \sum_{i=1}^{N} P_i^t U_i^t\right) \qquad \ldots(3.6)$$

Advantages:

1. The Lagrange Relaxation technique can be easily modified to model characteristics of specific utilities.
2. It can deal with different types of constraints very flexibly and it is relatively easy to add constraints.
3. It incorporates even those additional coupling constraints that have not been considered so far, very easily.
4. Lagrangian relaxation method is also more flexible than dynamic programming because no priority ordering is imposed.

5. It is computationally much more attractive for large systems.

Disadvantages:

1. Its weakness is that the optimal solution seldom satisfies the once relaxed coupling constraints.
2. Another weakness is the sensitivity problem that may cause unnecessary commitments of some units. Therefore only a nearly optimal feasible solution can be expected. However, the degree of sub optimality decreases as the number of units increases.

3.4 ECONOMIC DISPATCH VERSUS UNIT COMMITMENT

At this point, it will be good to emphasize the essential difference between the unit commitment and economic dispatch problem. The economic dispatch problem assumes that there are N units are already connected to the system. The purpose of economic dispatch problem is to find the optimum operating policy for these N units.

On the other hand, the unit commitment problem is more complex. It can be assumed that only N units are available and forecasting of the "to be served" demand has to be done. The question that is asked in the unit commitment problem area is approximated as follows,

"Given that there are a number of subsets of the complete set of N generating units that would satisfy the expected demand, which of these subsets should be used in order to provide the minimum operating cost".

This unit commitment problem can be extended over some period of time, such as 24 hours a day or 168 hours a week. Hence the unit commitment problem is much more difficult to solve. The solution method involves the economic dispatch problem as a sub problem. That is, for each of the subsets of the total units that are to be tested, for any given set of them connected to the load, the particular subset should be operated in optimally and economically. This will help in finding the minimum operating costs for that subset, but it will not specify which of these subsets is in fact the one that will give minimum cost over a period of time.

CHAPTER 4
FUZZY LOGIC

4.1 INTRODUCTION

Fuzzy logic has rapidly become one of the most among the present technologies for developing sophisticated control systems. Fuzzy logic addresses applications perfectly as it resembles human decision making power. It has the ability to generate precise solutions from certain or approximate information. It fills an important gap in engineering design methods that was left vacant by purely mathematical approaches (e.g. linear control design), and purely logic-based approaches (e.g. expert systems) in system design.

While other approaches require accurate equations to model real-world behaviors, fuzzy design can work well with the ambiguities of real-world human language and logic. It provides an intuitive method for describing systems in human terms and automates the conversion of those system specifications into effective models [13].

4.1.1 What does it offer?

The very first applications of fuzzy theory were primly industrial, such as process control for cement kilns. However, as the technology kept on developing, fuzzy logic was also used in more useful applications. In 1987, the first fuzzy logic-controlled subway was opened in Sendai in northern Japan. Here, fuzzy-logic controllers made subway journeys more comfortable with smooth braking and acceleration and all the driver just has to push the start button! Fuzzy logic was also put to work in elevators to reduce waiting time. Since then, the applications of Fuzzy Logic technology have virtually exploded, affecting all the day to day things.

4.2 BACKGROUND

Fuzzy logic was discovered by Lotfi A. Zadeh, a professor of UC Berkeley in California, known as the founder of fuzzy logic. He observed that conventional computer logic was incapable of manipulating data representing subjective or vague human ideas. Hence he designed fuzzy logic that allowed computers to determine the distinctions among data with shades of gray, quite similar to the process of human reasoning. In 1965, Zadeh published his seminal work on "Fuzzy Sets" which described the mathematics of fuzzy set theory. This theory proposed how to make the membership function (or the values False and True) operate over the range of real numbers [0.0, 1.0] and this way Fuzzy logic was now introduced to the world [18, 36].

4.3 What does FUZZY means?

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial true values between "completely true" and "completely false". As its name suggests, it is the logic underlying modes of reasoning which are approximate rather than exact. The importance of fuzzy logic is derived from the fact that most modes of human reasoning, common sense reasoning, are approximate in nature. The essential characteristics of fuzzy logic as founded by Zadeh Lotfi are as follows:

- In fuzzy logic, exact reasoning is viewed as a limiting case of approximate reasoning.
- In fuzzy logic, matter of degree plays an important role.
- Any logical system can be fuzzified.
- In fuzzy logic, knowledge is interpreted as a collection of elastic or, equivalently , fuzzy constraint on a collection of variables
- Inference is viewed as a process of propagation of elastic constraints.

4.4 FUZZY SETS

A paradigm is a set of rules and regulations which defines boundaries and helps in solving problems within these boundaries successfully. For example the use of transistors instead of vacuum tubes is a paradigm shift - likewise the development of Fuzzy Set Theory from conventional bivalent set theory is a paradigm shift.

Bivalent Set Theory can proved somewhat limiting while defining a 'humanistic' problem mathematically.

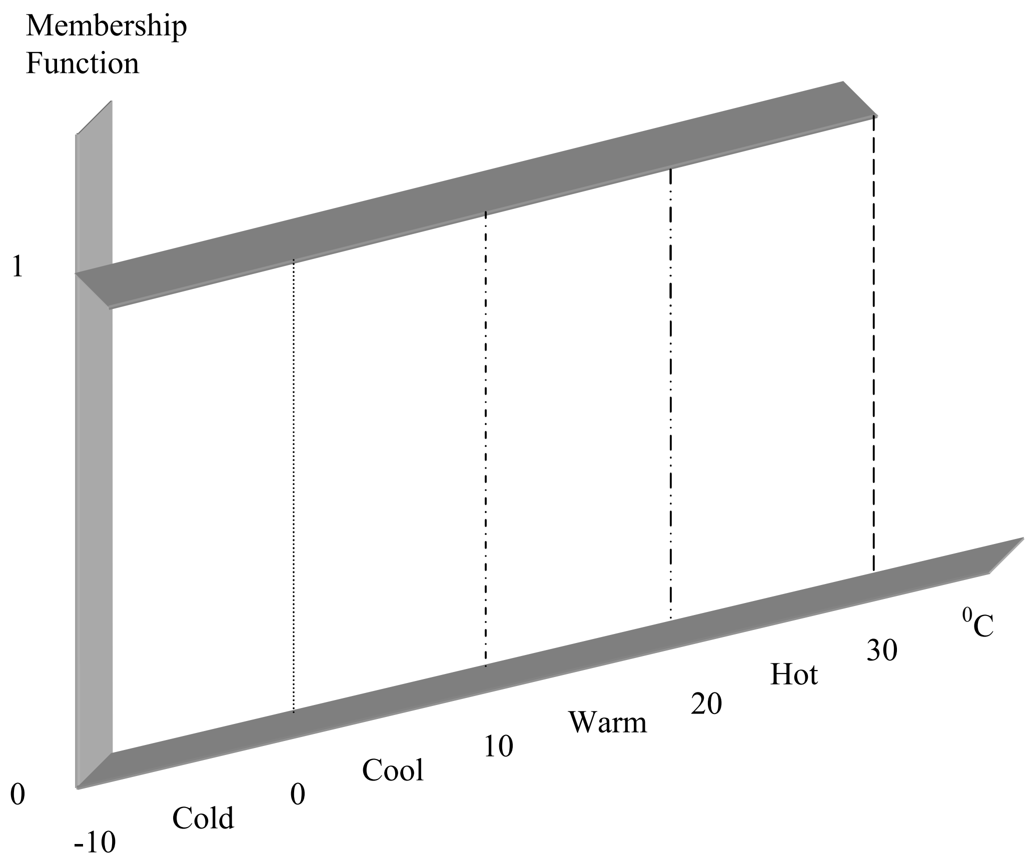


Fig 4.1: Bivalent sets to characterize the temperature of a room.

The most obvious limiting feature of bivalent sets that can be seen clearly from the diagram is that they are mutually exclusive - it is not possible to have membership of more than one set, for example opinion may vary as to whether 50 degrees Fahrenheit is 'cold' or 'cool'. Hence the expert knowledge we need to define our system is mathematically at odds with the humanistic world). Clearly, it is not accurate to define a transition from a quantity such as 'warm' to 'hot' by the application of one degree Fahrenheit of heat compared to this in the real world, a smooth (unnoticeable) drift from warm to hot would be visible. This natural phenomenon can be described more accurately by Fuzzy Set Theory.

Fuzzy Set theory involves the following Operations:

i. Union
ii. Intersection
iii. Complement
iv. De Morgan's Law
v. Associativity
vi. Commutativity
vii. Distributivity

4.4.1 Fuzzy Rules

Human beings make decisions based on rules. Although, we may not be aware of it, but whatever decisions are made are all based on computer like if-then statements. Foe example, if the weather is fine, then we may decide to go out. If the forecast says the weather will be bad today, but fine tomorrow, then we make a decision not to go today, and postpone it till tomorrow. Rules associate ideas and relate one event to another. Fuzzy machines, which always tend to mimic the behaviour of man, also work in the same way. However, the decision and the means of choosing that decision are replaced by fuzzy sets and the rules are replaced by fuzzy rules. Fuzzy rules also operate using a series of if-then statements. For instance, if X then A, if y then b, where A and B are all sets of X and Y. Fuzzy rules define fuzzy patches, which is the key idea in fuzzy logic [12].

4.4.2 Fuzzy Control

Fuzzy control, which directly uses fuzzy rules, is the most important application in fuzzy theory. Using a procedure originated by Ebrahim Mamdani in the late 70s, three steps are taken to create a fuzzy controlled machine:

1) Fuzzification (Using membership functions to graphically describe a situation)
2) Rule evaluation (Application of fuzzy rules)
3) Defuzzification (Obtaining the crisp or actual results)

Advantages:

i. Allows the use of vague linguistic terms in the rules.
ii. Fuzzy logic solutions are easy to verify and optimize.

Disadvantages:

i. It is difficult to optimize membership function.
ii. There are many ways of interpreting fuzzy rules, combining the output of several fuzzy rules and defuzzifying the outputs [12, 18].

4.5 UNIT COMMITMENT USING FUZZY LOGIC

In any power system, the load is dynamic in nature. It is 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. The load variation is continuous and the load must be met with the available resources economically. This is done by committing (switching ON) and decommitting (switching OFF) of the units in power station. By running only the most economic units, the load can be supplied to the best efficiency of unit operators. Thus committing the correct number and kind of units such that the load is met at least operating cost.

There have been many methods that are available to solve the unit commitment problem such that the Lagrangian method, Dynamic Programming (DP), branch and bound technique, simulated annealing, Priority listing and Advanced Priority listing method. The DP method based on priority list is flexible, but it computational time suffers from dimensionality. Lagrangian relaxation for UCP is superior to DP due to its higher solution quality and faster computational time. However, numerical convergence and solution quality of LR do not give satisfactory results in case identical units exit. These methods though may give results but does not give a qualitative interpretation of the results in terms of input variables. Hence a fuzzy logic technique is used in order to solve the problem of unit commitment. The use of fuzzy logic has received increased attention in recent years because of its usefulness in reducing the need for complex mathematical models in problem solving. Fuzzy logic employs linguistic terms, which deal with the casual relationship between input and output variables. Hence, it simplifies the approach for manipulating and solving many problems, particularly where the mathematical models are either not explicitly known or if known it is difficult to formulate them. It also attempts to quantify the linguistic terms so that the variables can be treated as continuous rather than discrete. Furthermore, Fuzzy logic is a technique, which approximates reasoning, while allowing decisions to be made efficiently [5, 8, 23].

4.6 FUZZY LOGIC IMPLEMENTATION

Fuzzy logic provides not only a meaningful and powerful representation for measurement of uncertainties but also a meaningful representation of vague concepts expressed in natural language. It is a mathematical theory, which encompasses the idea of vagueness when defining a concept or meaning. For example, there is uncertainty or fuzziness in the expression like ‘large’ or ‘small’, since these expressions are imprecise and relative. Hence the variables considered are termed ‘fuzzy’ as opposed to ‘crisp’. Fuzziness is simply one way of describing uncertainty. Such ideas are readily applicable to the unit commitment.

4.7 FUZZY UCP MODEL

The objective of every electric utility is to operate at minimal cost while meeting the load demand and spinning reserve requirements. In the present formulation, the fuzzy variables associated with UCP are

- Load demand (LD)
- Incremental fuel cost (IC)
- Power Generation (PG)

The load demand is taken to be fuzzy, as it is based upon the load to be served. Incremental fuel cost is also taken to be fuzzy, because the cost of fuel may change over a period of time, and may be different foe each unit. Further the start-up costs of the unit are assumed to be fuzzy, because some units take more time than others to be placed on line. Certain other variables, such as, minimum up and down times, spinning reserve and generator limitations, are considered as crisp variables in the unit commitment problem.

Uncertainty in fuzzy logic is a measure of nonspecificity that is characterized by possibility distributions. This is similar to the use of probability distributions, which characterize uncertainty in probability theory. The possibility distributions attempt to capture the ambiguity linguistically by describing the physical process variables.

4.7.1 Fuzzy Set Associated with Unit Commitment

After identifying the fuzzy variables associated with unit commitment, the fuzzy sets defining these variables are selected and are normalized between 0 and 1. This normalized value can be multiplied by a selected scale factor to accommodate any desired variable.

The sets defining the load demand as follows:

LD, MW = {Low, below average, Average, above average, High}

The incremental cost is stated by the following sets:

IC, Rs = {Zero, Small, large}

The power generation, chosen as the objective function, is given by:

PG, Rs = {Low, below average, Average, above average, High}

Based on the aforementioned fuzzy sets, the membership functions chosen for each input and output variables are shown in fig 4.7.2.1 to fig 4.7.2.3.

For convenience, a triangular shape is used to illustrate the membership functions considered here. Once these sets are established, the input variables are then related to the output variable by IF-THEN rules.

4.7.2 Fuzzy *IF-Then* Rules

If fuzzy logic based approach decisions are made by forming a series of rules using if-then statements that relate the input variables to the output variables, then for each rule the *IF* (condition) is antecedent to the *Then* (consequence) of each rule. Each rule in general can be represented in the following manner:

IF (antecedent) *Then* (consequence)

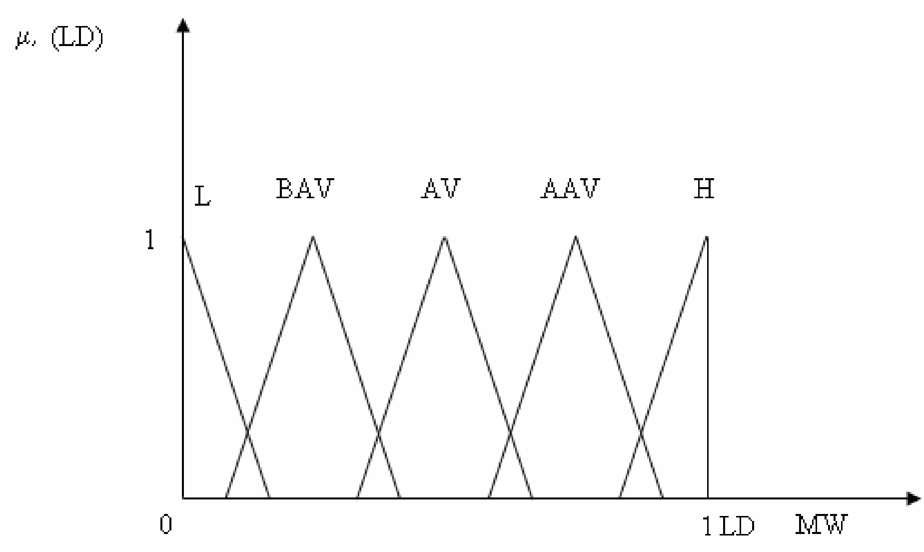


Fig 4.2: Membership function of Load demand

Where

L : Low

BAV : Below average

AV : Average

AAV : Above average

H : High

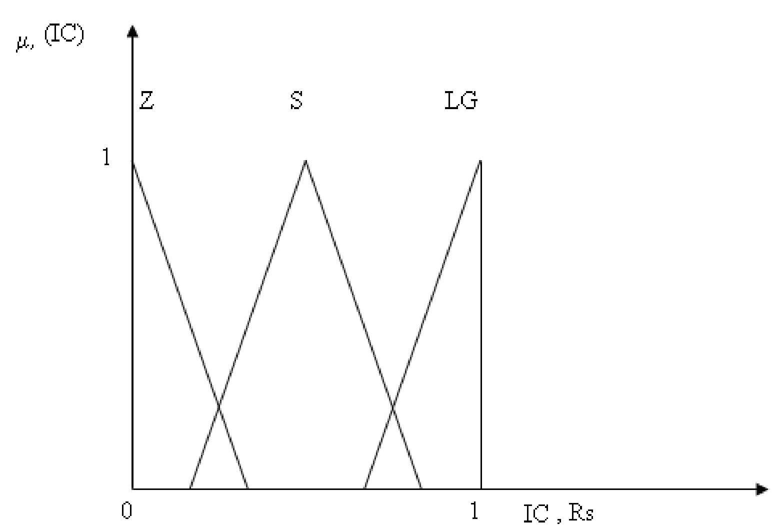


Fig 4.3: Membership function of Incremental fuel cost

Where

Z : Zero

S : Small

LG: Large

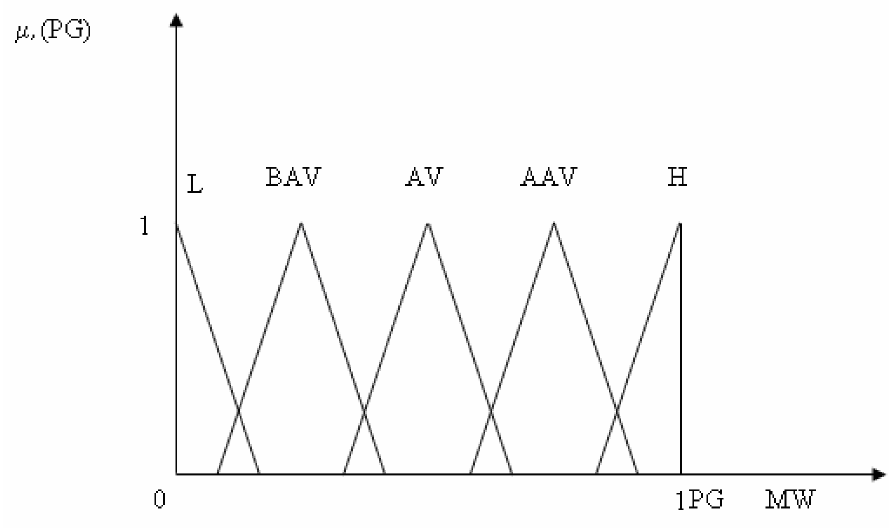


Fig 4.4 Membership function of Power generation

Where

L : Low

BAV : Below average

AV : Average

AAV : Above average

H : High

The load demand and incremental fuel cost are considered as input variables and power generation is treated as the output variable. This relation between the input variables and output variables is given as:

Power generation = {Load demand} and {Incremental fuel cost}

In fuzzy set notation this is written as,

$PG=LD\cap IC$

Hence, the membership function of the power generation, μPG is computed as follows.

$\mu PG = \mu LD \cap \mu IC$

$\mu PG = \min \{\mu LD, \mu IC\}$

where μLD and μIC are memberships of load demand and incremental fuel cost respectively.

Rule for the load demand can be written as follows:

If the load demand is low and Incremental fuel cost is small then power generation is low.

After relating the input variable to the output variable, the fuzzy results must be defuzzified through what is called as defuzzification process to achieve crisp numerical values. [24-26]

4.7.3 Defuzzification Process

One of the most commonly used methods of defuzzification is the centroid or centre of gravity method. Using this method, the power generation is achieved as follows

$$\text{P}owerGeneration = \frac{\sum_{i=1}^{n} \mu\left(PG\right)_i * PG_i}{\sum_{i=1}^{n} \mu\left(PG\right)_i} \qquad \ldots(4.1)$$

Where $\mu\left(PG\right)_i$ is the membership value of the clipped output; PG_i, the quantitative value of the clipped output and n is the number of points corresponding to quantitative value of the output.

CHAPTER 5
PROBLEM FORMULATION

5.1 Thermal Unit Commitment Formulation

As the size of the system grows and more complicated constraints are imposed, it is often insufficient to rely on human intuition solely achieving for the optimal solution. So, more rigorous programming techniques are utilized. The analytical methods treat the unit commitment problem as a mixed integer/real variable optimization problem. The existing methods, such as dynamic programming, Priority listing, and Lagrangian relaxation, provide effective alternatives for evaluating commitment plans. However, they demand a vast amount of calculating power.

Unit commitment problem is formulated as the production cost of units considering the fuel cost and the transition (start-up) cost [1, 6].

Fuel cost model

The fuel cost is the production cost of operating generators to meet the load demand of a system during a specified time period. This cost depends on the heat rate, fuel price (constants) and unit-load curves.

A unit-load curve represents the incremental or total operating cost of a generating unit as the function of megawatt power level. For modeling, the curve, the incorporation of minimum and maximum limits is essential. The cost curve is assumed to be non-linear. The curves are approximated by the following quadratic function

$$F(P_{gi}) = \sum_{i=1}^{NG} (a_i P_{gi}^2 + b_i P_{gi} + c_i) Rs/hr \qquad ...(5.1)$$

Start up cost model

A simplified time dependent start up cost is taken as follows:

Hot start up cost if down time is less than or equal to cold start hours

Start up cost=cold start cost, otherwise.

The function to be minimized for unit commitment problem can be expressed in mathematical form as follows:

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\left[F_i\left(P_i^t\right)+startup\cos t_{i,t}\right]U_i^t = F\left(P_i^t,U_i^t\right) \qquad \ldots(5.2)$$

Transmission losses

Loss coefficients method is used to calculate the total transmission losses for generator economic allocation. These coefficients or constants are in fact not constants as such but are found to depend on the loading conditions as well as the configuration of the power system.

$$P_L = \sum_{i=1}^{k}\sum_{j=1}^{k} P_{Gi}B_{ij}P_{Gj} + \sum_{i=1}^{k} B_{0i}P_{Gi} + B_{00} \qquad \ldots(5.3)$$

Subject to the following major constraints:

1. Power balance constraint:

   Generation should meet the load demand and the spinning reserve plus transmission losses.

   $Pi = PD + spinning\_reserve + losses$

   where Pi is the real power generation of ith plant and PD is the total power demand.

2. Power generation limits:

   These limits define the region within which a unit must be dispatched.

   $P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}$

   where $P_{gi}^{\min}$, the lower limit of the real power output of ith unit and $P_{gi}^{\max}$,the upper limit of the real power output of the ith unit.

3. Minimum up time:

   This constraint signifies the minimum time for which a committed unit should be turned off and removed from online.

4. Minimum down time:

   This constraint signifies the minimum time for which a decommitted unit should be turned on and brought on-line.

5. Spinning reserve constraints:

   Spinning reserve is the term used to describe the total amount of generation available from all the units synchronized on the system minus the present load plus losses being incurred. Spinning reserve must be carried so that the loss of one or more units does not cause too far a drop in system frequency [5, 25].

5.2 ALGORITHM OF UNIT COMMITMENT PROBLEM

1. Read the constant a_i, b_i and c_i, loss coefficients B_{ij}, B_{0i}, constant B_{00}, power demand P_D, maximum P_{Gi}^{max}, minimum P_{Gi}^{min} generators real power limits, Start up costs (Hot + Cold), No Load cost, Spinning reserve, Load data and Generator data.
2. Initialize.
3. Consider hour 1.
4. Assume a suitable value of $\lambda = \lambda_0$. Calculate $P_{G1}, P_{G2}, \ldots\ldots, P_{Gi}$ based on equal incremental cost.
5. Calculate the generation at all buses using

$$P_{Gi} = \frac{1 - B_{0i} - \frac{b_i}{\lambda} - \sum_{j=1}^{k} 2B_{ij}P_{Gj}}{\frac{2a_i}{\lambda} + 2B_{ii}} \quad i = 1, 2, \ldots\ldots, k \qquad \ldots(5.4)$$

6. Calculate the losses using the relation

$$P_L = \sum_{i=1}^{k}\sum_{j=1}^{k} P_{Gi}B_{ij}P_{Gj} + \sum_{i=1}^{k} B_{0i}P_{Gi} + B_{00} \qquad \ldots(5.5)$$

7. Calculate,

$$\Delta P = \sum_{i=1}^{k} P_{Gi} - P_D - P_L \qquad \ldots(5.6)$$

8. Update λ as $\lambda^{(k+1)} = \lambda^{(k)} - \Delta\lambda^{(k)}$, where $\Delta\lambda$ is the step size.
9. Update new power demand using spinning reserve and transmission losses, P_D^{new}
10. For the new power demand display all the feasible combinations.

11. The Start up cost of a unit is independent of the time it has been off line (it is a fixed amount).
12. Satisfy operating constraints and spinning reserve requirements.
13. Calculate cost of generation with values of powers using the fuel cost and extra cost for all states FC, HS and CS.

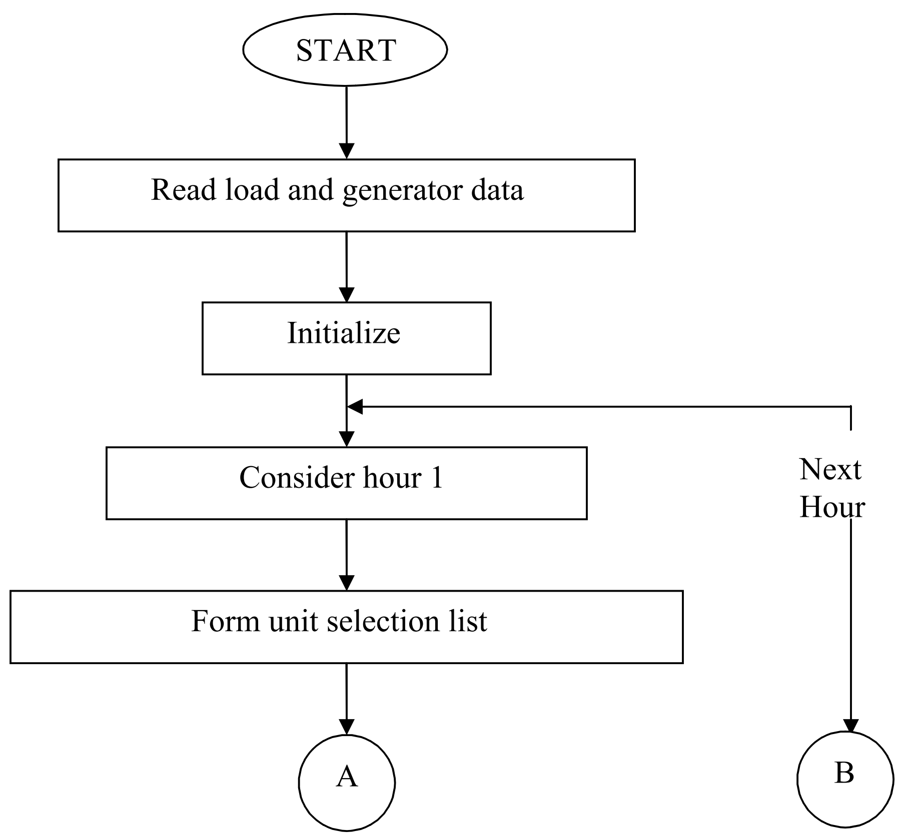
$$F_{cost} = S_{cost} + (no\,load\_cost) \quad \ldots(5.7)$$

14. Compute total cost, store most economical strategy and do for all states.

$$F_{cost} = \min\left[S_{cost} + (no\,load\_cost)\right] \quad \ldots(5.8)$$

15. Save lowest cost strategies.
16. Trace optimal schedule.

5.3 FLOWCHART OF UNIT COMMITMENT PROBLEM



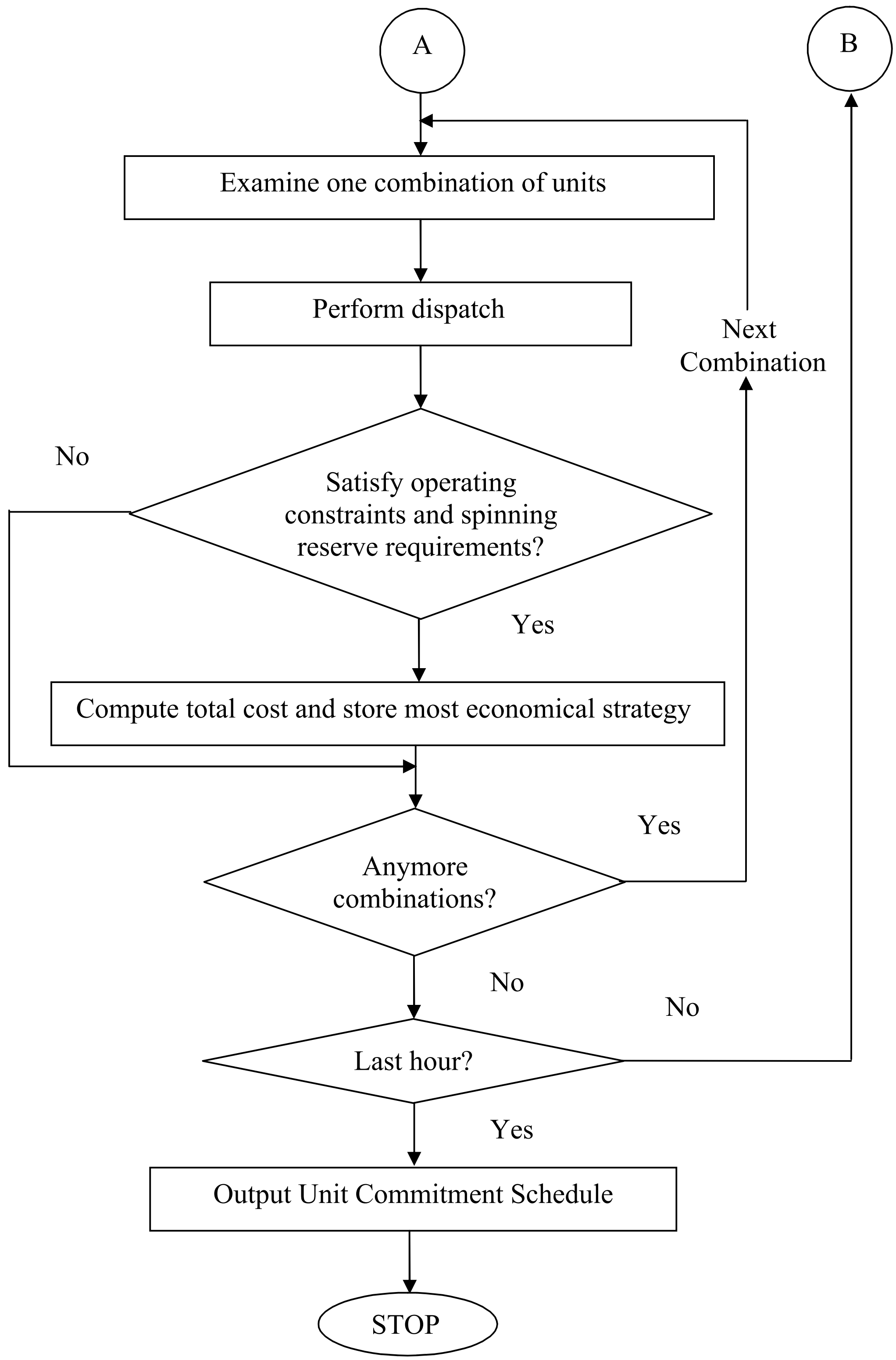


Fig 5.1: Simplified Flow Chart of Unit Commitment Procedure

A recursive search technique, called dynamic programming, is used to find the most economic feasible commitment schedule. The outline of the approach is shown by the flowchart in figure 5.1

The unit commitment procedure is divided into two major parts. The first involves the formation of a unit selection list (figure 5.1), and the other part consists of a search technique which determines optimal feasible schedules for a given study period.

5.4 PROPOSED FUZZY LOGIC ALGORITHM

1. Identify fuzzy input and output variables. The identified fuzzy input and output variables are load demand, incremental cost and power generation of three units.
2. Relate the fuzzy input and output variables using fuzzy rules (If-then) like if the load demand is low and incremental cost is low then the power generation of unit 1 is low, power generation of unit 2 is low and power generation of unit 3 is low.
3. Observe the results that satisfy more than one rule.
4. Defuzzify the output variable (power generation).
5. Then from the output variable cost is obtained
6. Repeat steps 2 to 5 for all the possible applied rules.

5.5 FLOWCHART OF THE PROPOSED FUZZY LOGIC ALGORITHM

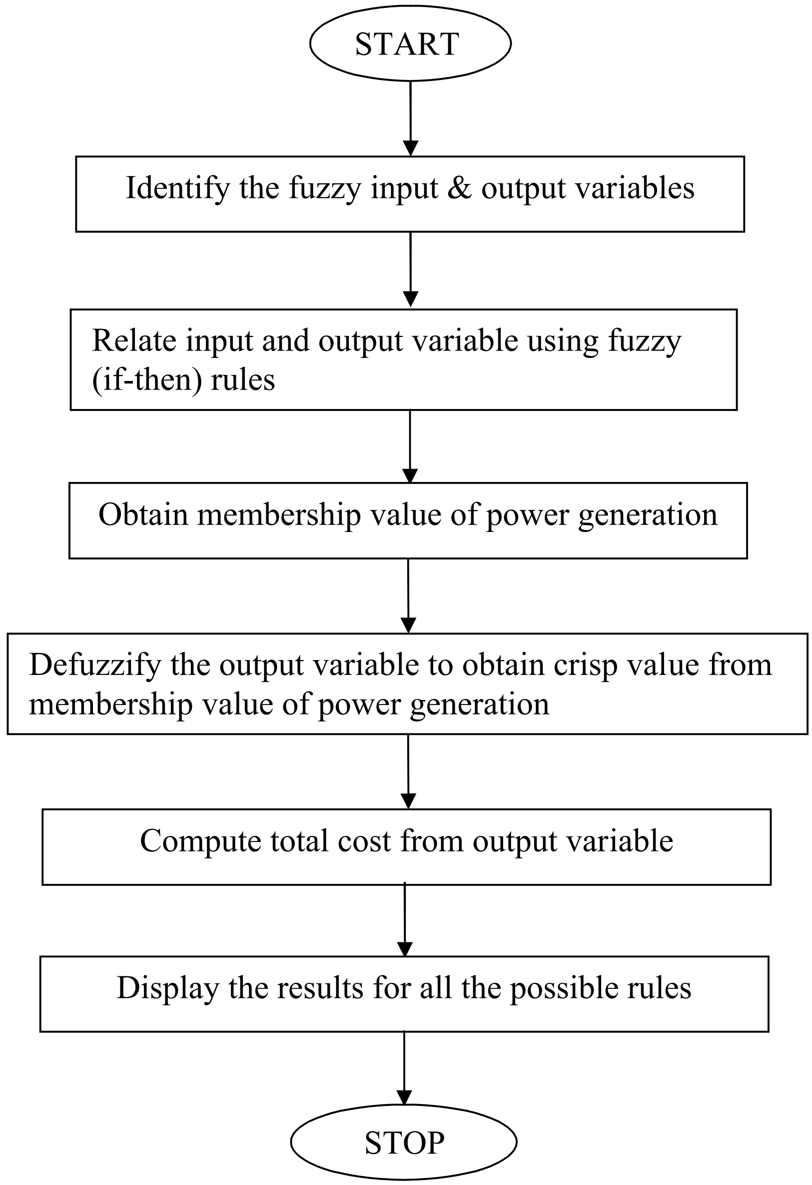


Fig 5.2: Flowchart of the Proposed Fuzzy Logic Algorithm

CHAPTER 6
RESULTS AND DISCUSSION

6.1 RESULTS OBTAINED BY CONVENTIONAL DYNAMIC PROGRAMMING APPROACH

The approach mentioned in Chapter 5 is applied to a system comprised of 3 generating units whose input data like load pattern of 24 hrs, cost functions, unit characteristics and B-coefficients matrix are shown in APPENDIX A.

Costs obtained by using the Load pattern shown in table A1 by conventional dynamic programming (ignore losses and spinning reserve) are shown in Table 6.1:

Table 6.1: Costs obtained by using the Load pattern shown in table A1 by conventional dynamic programming (ignore losses and spinning reserve)

Load demand (MW)	Unit combinations	Dynamic approach
400	1 0 0	440
	1 1 0	**432.76**
	1 0 1	887.93
	0 1 1	895.76
450	1 1 0	**485.65**
	1 0 1	699.07
	0 1 1	674.05
700	1 1 0	750.089
600	1 0 0	660
	1 1 0	**644.3**
	1 0 1	667.5
550	1 0 0	605
	1 1 0	**591.4**

	1 0 1	611.4
500	1 0 0 1 1 0 1 0 1 0 1 1	550 538.5 555.2 **527**
750	1 1 0	802.975
650	1 1 0 1 0 1	**697.2** 723.6

According to Power generation-load balance constraint,

Generation should meet the load demand and the spinning reserve plus transmission losses. In this work, both are considered.

$Pi = PD + spinning\_reserve + losses$

Spinning reserve is taken as 50 MW (constant)

Transmission losses have been calculated 17.86699 MW by using Table A4 and equation (5.5).

Costs obtained by conventional dynamic approach (considering losses and spinning reserve) are shown in Table 6.2

Table 6.2: Costs obtained by conventional dynamic approach (considering losses and spinning reserve)

Load demand (MW)	Unit combinations	Dynamic approach
467.86	1 0 0 1 1 0 1 0 1	514.65 **504.55** 964.12
517.86	1 0 0 1 1 0 1 0 1	569.65 **557.43** 775.26
767.86	1 1 0	1397.13

667.86	1 1 0	716.09
617.86	1 1 0 1 0 1	**663.21** 687.54
567.86	1 0 0 1 1 0 1 0 1	624.65 **610.32** 632.20
817.86	1 1 0	1506.96
717.86	1 1 0	2275.95

A MATLAB code has been developed for solving Fuzzy logic based unit commitment problem.

6.2 RESULTS OBTAINED BY FUZZY LOGIC

The first step in solving a problem using fuzzy logic is identification of the fuzzy variables. The fuzzy variables associated with unit commitment in this work are:

1. Load demand
2. Incremental cost
3. Power generation

After the identification of the variables associated with unit commitment, the fuzzy set associated must be formulated. This forms the second step in fuzzy based problem. The selected fuzzy sets are normalized between 0 and 1. Load demand and incremental cost are the input variables and the power generation is the output variable (PG1, PG2, PG3 is taken as the output variables of three generating units). The fuzzy sets associated with the three fuzzy variables are given below:

1. Power demand: LD
   LD (MW) = {low (L), normal (N), high (H)}
2. Incremental cost: IC
   IC (Rs/MWhr) = {low (L), normal (N), high (H)}
3. Power generation: PG1
   PG1 (MW) = {very low (VL), low (L), high (H), very high (VH)}
4. Power generation: PG2
   PG2 (MW) = {very low (VL), low (L), high (H), very high (VH)}

5. Power generation: PG3

   PG3 (MW) = {very low (VL), low (L), high (H), very high (VH)}

Based on the fuzzy sets, the membership functions are chosen for the fuzzy variables.

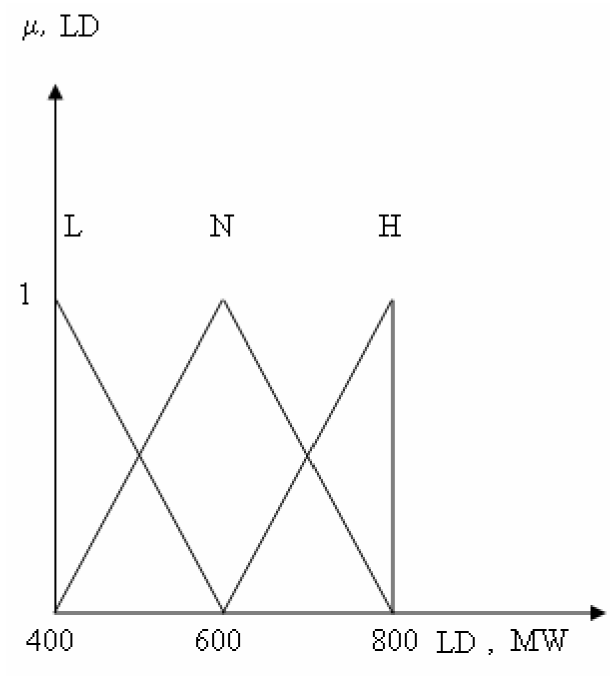


Fig 6.1: Membership function of load demand

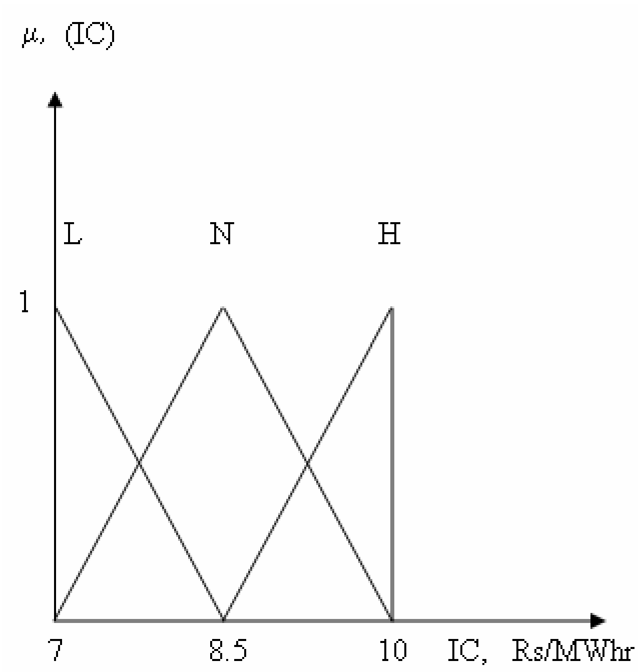


Fig 6.2: Membership function of Incremental cost

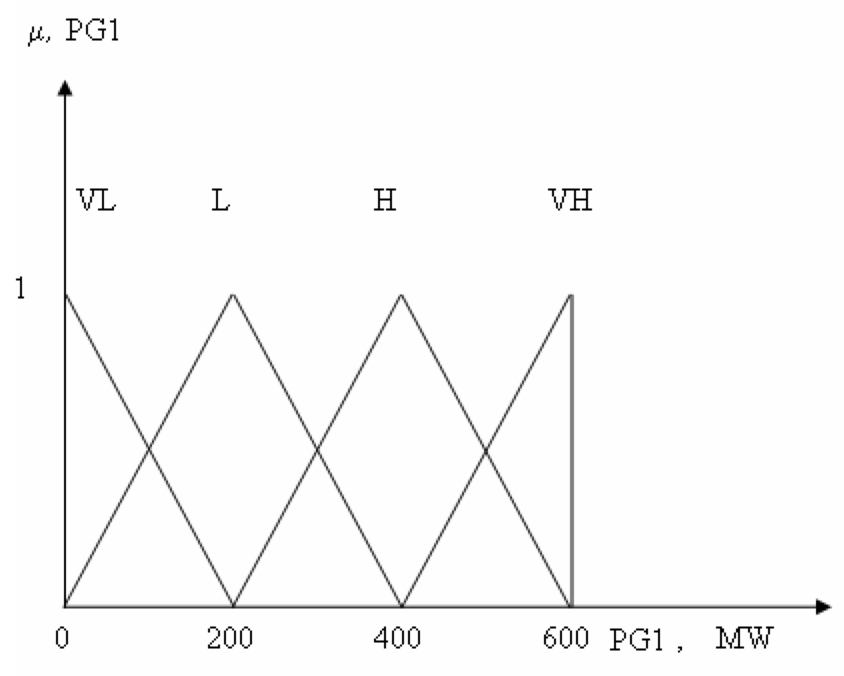


Fig 6.3: Membership function of power generation of unit 1

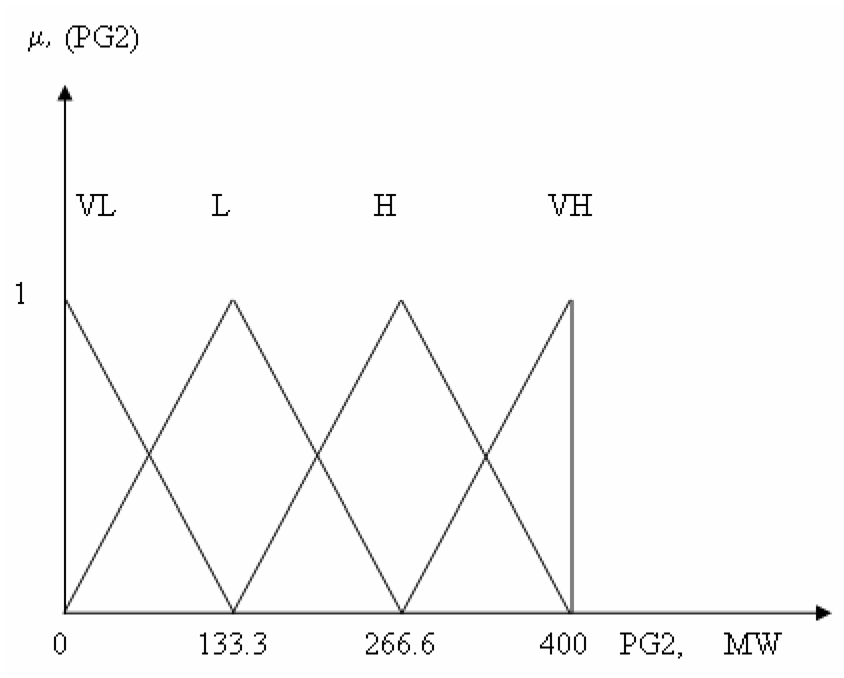


Fig 6.4: Membership function of power generation of unit 2

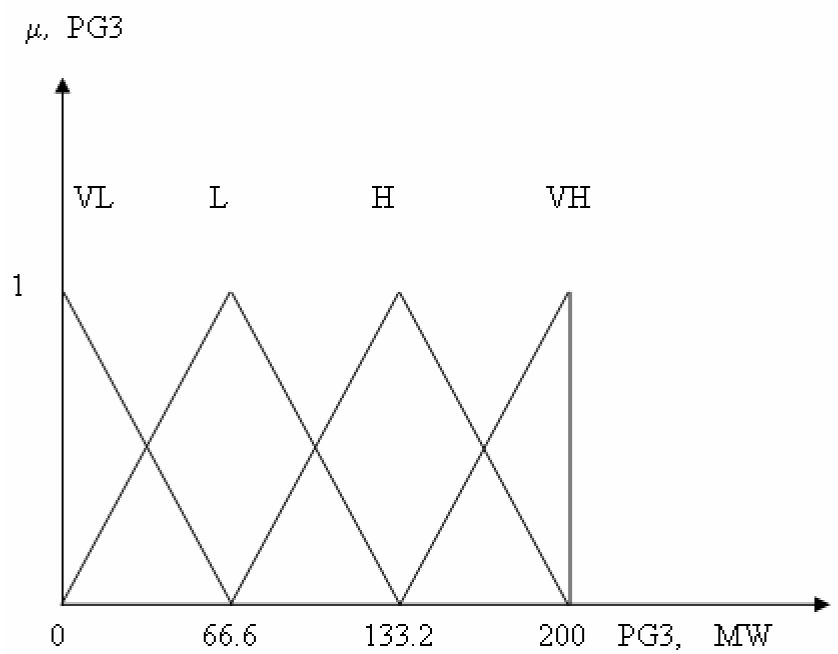


Fig 6.5: Membership function of power generation of unit 3

Fuzzy rules applied to the problem:

For (400<=LD<=600) & (7<=IC<=8.5), rule 1, rule 2, rule 3, rule 8 and rule 12 are affected.

For (600<=LD<=800) & (7<=IC<=8.5), rule 6 and rule 7 are affected.

For (600<=LD<=800) & (8.5<=IC<=10), rule 4, rule 5, rule 9 and rule 10 are affected.

These rules are implemented in MATLAB program.

The results obtained using the fuzzy logic approach (considering all the three units committed) is shown in Table 6.3

Table 6.3: The results obtained using the fuzzy logic approach (considering all the three units committed)

Load demand (MW)	Total cost (Rs)
400	431.2306
450	486.2506
700	761.6675
600	649.9988

550	598.3325
500	540.8338
750	804.9975
650	704.999
Total cost of operation (Rs)	4978.3103

A comparison of the results in Table 6.2 and Table 6.3 indicates that fuzzy logic gives a lesser operating cost and dynamic approach gives more operating cost.

6.3 CONCLUSION

This thesis work is an attempt to compare the total cost obtained by the conventional dynamic programming and fuzzy logic technique applied to it. An effective, robust UC solution is a necessary contribution to the operating On/Off plans of the generating units. Unit commitment is a problem where ambiguity exists and such problems can be easily addressed to using fuzzy logic. As the size of the system grows and more complicated constraints are imposed, it is often insufficient to rely on human intuition to achieve the optimal solution. Hence, fuzzy logic is implemented for solving the Unit Commitment problem. It was demonstrated that Unit Commitment problem can be solved using fuzzy logic and this method can be applied to any no. of units, each with different operating costs. From this approach, it can be concluded that the outcomes are easily understood in terms of the logical representation of the rules.

For costs obtained by conventional DP, the ON/OFF states of the units have been considered in order to meet to the load demand whereas, for cost obtained by fuzzy logic technique, only the ON state of units have been assumed. After assessment, it is observed that both, costs obtained and computation time by conventional Dynamic Programming is more as compared to Fuzzy logic. Hence, Fuzzy logic is found to be very efficient as compared to conventional Dynamic Programming.

6.4 FUTURE SCOPE

The proposed problem can also be solved with other artificial intelligence technique like Neural network, Evolutionary programming and Genetic algorithm etc.The above problem can also be solved if the system complexity increases i.e. either by increasing the no. of units or adding the no. of constraints. We can also formulate the proposed technique by committing each unit separately.

APPENDIX A

For solving the problem using conventional Dynamic programming initial conditions are taken as follows:

1. Unit 1 and unit 2 are initially ON.
2. Unit 3 is OFF from the last three hours
3. Initially losses and spinning reserve are ignored.

Gap is of 3hrs, load pattern starts from 12midnight.

Table A1: Load Pattern

Hrs	Load (MW)
12-3	400
3-6	450
6-9	700
9-12	600
12-3	550
3-6	500
6-9	750
9-12	650

Table A2: Cost functions

Unit no.	a_i (Rs/MW^{2}h)	b_i (Rs/MWh)	c_i (Rs/h)
1	0.00142	7.2	510
2	0.00194	7.85	310
3	0.00482	7.97	78

Table A3: Unit characteristics

Unit no.	Max (MW)	Min (MW)	No load cost(Rs/hr)	Start up cost,Rs (hot)	Start up cost, Rs (cold)	Fuel cost (Rs/MW)
1	600	150	213	250	400	1.1
2	400	100	175	175	300	1.0
3	200	50	115	100	200	1.2

Table A4: The B- coefficients (MW^{-1}) Matrix

0.0001363	0.0000175	0.0001839
0.0000175	0.0001545	0.0002828
0.0001839	0.0002828	0.0016147

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