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Fuzzy Logic Based Solution to the Unit Commitment Problem

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة عمادة الدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ **محمد مسعود عبد الحميد حجو** لنيل درجة الماجستير في **كلية *الهندسة* قسم الهندسة الكهربائية–أنظمة التحكم** وموضوعها:

Fuzzy Logic Based Solution to the Unit Commitment Problem

وبعد المناقشة العلنية التي تمت اليوم الاثنين 19 ذو القعدة 1432هـ، الموافق 2011/10/17م الساعة الثانية ظهرًا، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

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وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في **كلية *الهندسة*/ قسم الهندسة الكهربائية– أنظمة التحكم.**

واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق ،،،

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إنه من سليمان وإنه

بسم الله الرحمن الرحيم

﴿وَقُل رَّبِّ زِدْنِي عِلْمًا﴾

[طه: 114]

DEICATION

To the teacher of the world, leader of the nation and mercy of Allah to mankind, Prophet Muhammad peace be upon him

To my lovely parents who are honor by this moment

To the memory of my beloved sister, I ask Allah to accept her in the paradise, Alaa'

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I address my sincere gratitude to Allah as whenever I faced any problem I used to pray to God to help me and He always was there protecting and saving me. Then, I would like to express my deep gratitude to my advisor Dr. Assad Abu-Jasser, who spared much time in supporting me with all concern. I also want to thank Dr. Hatem Elaydi and Dr. Basil Hamed for their valuable role and comments throughout my research work and for agreeing to take part in my defense.

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ABSTRACT

The aim of the unit commitment is to obtain the best combination of generation units to be turned on/off for each power demand of the daily load curve in order to ensure economic scheduling of power generation to minimize the production cost while satisfying a variety of constraints. Different techniques are available to handle the unit commitment problem to provide quality solutions in order to increase the potential savings of the power system operation such as deterministic and stochastic or modern search techniques. In this study, a proposed approach based on the fuzzy logic to handle the unit commitment problem is introduced where the suggested method is used to formulate the problem, to provide superior detection of the logic rules required, and to develop adequate algorithm that better solves them. To test the validity and effectiveness of the proposed approach, the outcomes of this approach are compared with those obtained by the dynamic programming which is the mostly used method to handle the unit commitment problem. Firstly, the production costs obtained by the fuzzy-logic and the dynamic programming for the same unit combination at each time interval loading are compared and secondly, the production costs of the fuzzy-logic and the dynamic programming are compared when both methods are employed separately to provide unit combination and production costs for each time interval. To undertake this study, two models of the Tuncbilek Thermal Power Plant in Turkey are selected. The first model consists of four generation units while the other consists of ten units. The load demand is assumed to vary over eight time periods for the four-unit model while it is assumed to vary on an hourly basis during the course of the day for the ten-unit model. The fuzzy logic approach has been successfully implemented to both models and the results have shown that the fuzzy-logic performs better than the dynamic programming in all cases of comparison.

مُلخص الدراسة

إن الهدف من unit commitment هو الحصول على أفضل توزيع لوحدات توليد القدرة الكهربائية بحيث يتم تشغيل و فصل الوحدات لتغذية الحمل المطلوب حسب منحنى الحمل اليومي من أجل ضمان جدولة اقتصادية لتوليد القدرة الكهربائية لتقليل تكاليف الإنتاج مع ضمان تحقيق مجموعة متنوعة من القيود . هناك العديد من التقنيات المستخدمة للتعامل مع هذه المشكلة. و من هذه الطرق **الحلول التقليدية** و **تقنيات البحث الحديثة. في هذه الدراسة، يتم تقديم طريقة جديدة** مقترحة تعتمد على Fuzzy Logic للتعامل مع مشكلة unit commitment حيث يتم استخدام الأسلوب المقترح لصياغة المشكلة، و لتقديم وصف متطور من قواعد Fuzzy المطلوبة، و وضع وصف خوارزمي من شأنه حل المشكلة على نحو أفضل من الطرق السابقة. و لاختبار صلاحية وفعالية الطريقة المقترحة، سيتم تقديم مقارنة بين النتائج التي يتم الحصول عليها من هذه الطريقة مع تلك التي يتم الحصول عليها من Dynamic Programming و هي الطريقة التي تستخدم غالباً للتعامل مع مشكلة unit commitment. و في البداية، تمت مقارنة تكاليف الإنتاج التي تم الحصول عليها بواسطة Fuzzy Logic مع تلك التي تم الحصول عليها بواسطة Dynamic Programming عند نفس التوزيع للوحدات في كل فترة من فترات التشغيل. و كذلك تمت مقارنة تكاليف الإنتاج التي تم الحصول عليها من Fuzzy Logic و Dynamic Programming عند تشغيل وحدات مختلفة لكل فترة زمنية. و لإجراء هذه الدراسة تم اختيار نموذجين مختلفين من محطة Tuncbilek التركية لتوليد القدرة الكهربائية. النموذج الأول يتكون من أربع وحدات توليد في حين يتكون الآخر من عشر وحدات. بحيث أن الحمل المطلوب يومياً من نموذج الوحدات الأربعة موزعا على ثمانية فترات زمنية متساوية, في حين أن الحمل المطلوب يومياً من نموذج الوحدات العشرة موزعا على أربع و عشرين فترة زمنية متساوية. وقد تم تطبيق تقنية Fuzzy Logic بنجاح على النموذجين و أظهرت النتائج أن التقنية الجديدة بواسطة Fuzzy Logic كان أداؤها أفضل من Dynamic Programming في كلتا الحالتين.

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CHAPTER 1
INTRODUCTION

1.1 Overview

Electric power generation plants contain several generation units that can be turned on/off to meet the ever changing power demand during the course of the day. Load variations have different patterns where the variations in summer are different than those in winter and in holidays are different than those in working days. Load curve is a plot of the power demand variations versus time during the course of the day. The electric power generation at power plants must always be capable of meeting these variations while satisfying a number of operation constraints. A suitable number of generation units are turned on/off to satisfy the power demand at all times. Unit Commitment (UC) is the problem of determining the schedule of generating units within a power plant subject to device and operating constraints. The decision process selects units to be turned-on or turned-off, the type of fuel, the power generation for each unit, the fuel mixture when applicable, and the reserve margins [1, 2]. So attention is increased to how operators in power stations could give a good plan for on-off status of units over a predicted time period. As the total load of the power system varies throughout the day and reaches different peak values from time to another. The electrical utilities have to decide in advance which generators to start-up and when to connect them to the network and the sequence in which the operating units should be shut down. The computational procedure for making such decisions is called unit commitment, and a unit when scheduled for connection to the system is said to be committed. To solve the unit commitment problem, the power demand over the operation periods is divided into discrete stages or subintervals and considering the predicted demand of the system to be constant over each interval. The unit commitment procedure then searches for the most economic feasible combination of the generating units to serve the forecasted load of the system at each stage of the given load curve.

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

Several solution strategies have been proposed to provide quality solutions to the UC problem to increase the potential savings of the power system operation. These include deterministic and stochastic or modern search approaches. Deterministic approaches include the priority list method, dynamic programming, Lagrangian Relaxation, and the branch-bound methods. Although these methods are simple and fast, they suffer from numerical convergence and solution quality problems [3]. Modern techniques such as fuzzy logic, genetic algorithms, evolutionary programming, simulated annealing, ant colony optimization, and tabu search are able to overcome the shortcomings of traditional optimization techniques. These methods can handle complex nonlinear constraints and provide high quality solutions. This formulation significantly reduces the number of decision variables and hence can overcome the disadvantages of stochastic search algorithms for UC problems.

Meeting load demands on the power supply system requires a sufficient number of generating units be committed to supply the required load and also owing to the tremendous expenses involved in unit commitment, the electric utility must determine which generators are the most economical to operate and the combinations of units that should be committed to meet a given load demand. Problems associated with unit commitment have generally been difficult to solve because of the uncertainty of particular aspects of the problem [4]. For example, the availability of fuels, imprecise load forecasts, variable costs affected by the loading of generating units of different fuels and losses caused by reactive power flows are some of the unpredictable issues. The considered problem is the commitment of fossil-fuel units which have different production costs because of their dissimilar efficiencies, designs, and fuel types. Although there are other factors of practical significance which determine when units should be scheduled for on and off status to satisfy the operating needs of the system, economics of operation is of a major importance. So, the unit commitment plans for the best set of units to be available to supply the predicted load of the system over a future time period.

In order to reach a feasible solution to this economic puzzle, different constraints must be considered such as spinning reserve, thermal unit constraints, must run units, fuel constraints, power generations load balance, security constraints and other operating constraints. Thermal constraints such as minimum up time and minimum down time, crew constraints and startup costs maybe require attention, since thermal units can suffer only gradual variations in temperature and pressure.

Fuzzy logic represents an effective alternative to conventional solution methods as dynamic programming because it attempts to quantify linguistic terms so that the variables can be treated as continuous rather than discrete. A fuzzy approach provides a means for the qualitative association of data. Hence, because of simplicity and less parameter tuning, fuzzy logic based approach is used for solving the unit commitment problem.

1.2 Statement of Problem

The major objective of this thesis is to demonstrate that, if the problem of unit commitment can be described linguistically then such linguistic descriptions can be translated into a solution that yields similar results or maybe better compared to other techniques. Hence, the problem to be dealt with is to examine and validate a proposed approach based on fuzzy logic that will be applicable to solve unit commitment problem to find the generation scheduling such that the total operating cost can be minimized while subjected to a variety of constraints. So, a set of linguistic fuzzy logic rules will be developed to establish the relationship between the inputs and the output.

Therefore, suitable model must be selected that have a proper number of generating units, characteristic of each unit is available and have a clearly load profile. Then, the unit commitment problem has to be translated into mathematical model or formulation mode to be dealt by the computer that will be used to develop a program capable of validating the fuzzy logic approach feasibility. Thus, the proposed technique is applied to two different thermal power plants with different number of generation units and power demand stages. The first plant consists of four units and the power demand is divided into eight periods over the 24-hours of the day while the second one consists of ten units and the power demand is divided into 24 periods. Hence, more realizable results will be generalized when the presented algorithm applied on four unit plant over eight period daily load demand and over twenty four hours for ten unit plant. Then the results obtained will be documented, graphed, and compared to highlight the merits of the demonstrated fuzzy logic approach.

1.3 Thesis Organization

This thesis is organized into seven chapters to report the whole research activities and to analyze and discuss the results. Each of the following paragraphs generally describes the contents of each chapter. Chapter-1 presents an overview on the unit commitment, statement of problem to be handled and discussed also the organization of the thesis. Chapter-2 talks about load curve and demand variations over a period of one day. In chapter-3 a brief literature review covering the solution methodologies of the unit commitment is introduced, along with thesis objective and the author contribution. Chapter-4 presents an overview of the unit commitment problem and conventional solution method with an observation on their advantages and disadvantages with a brief description of economic dispatch calculations by equal incremental cost criteria. Chapter-5 covers the concept of fuzzy logic and demonstrates fuzzy logic approaches to solve unit commitment problem and at the end, case studies are being applied. Chapter-6 presents the general conclusions and recommendations.

CHAPTER 2
LOAD CURVES

2.1 Introduction

The power station is constructed, commissioned and operated to supply required power to consumers with generators running at rated capacity for maximum efficiency. The fundamental problem in generation, transmission and distribution of electrical energy is the fact that electrical energy cannot be stored. It must be generated, transmitted and distributed as and when needed [1]. This chapter looks at problems associated with variable loads on power stations, and discusses the complexities met in deciding the make, size and capacity of generators units that must be installed in a power plant to successfully meet these varying energy demands on a day to day basis.

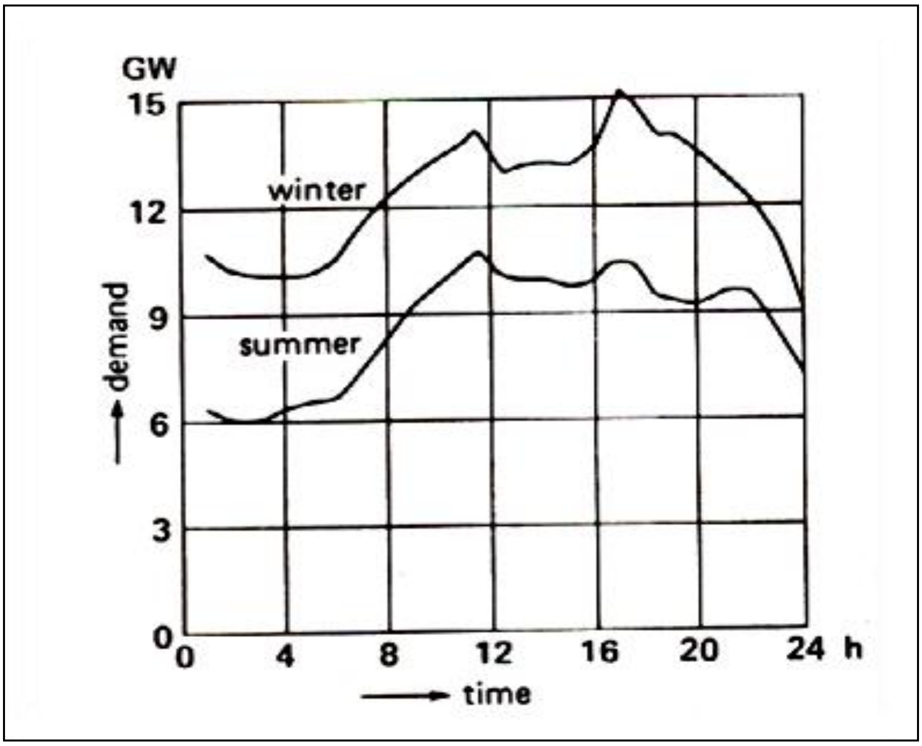


Figure 2-1: Daily load curve of a certain power system.

The load on a power station varies from time to time due to uncertain demands of consumers as shown in the Figure (2-1). Energy demand of one consumer at any given time is differs from the energy demand of another consumer. This results in the total demand on the power station to vary over a given period of time and may require the following:

- Additional generating units to meet demand.
- Increase in production cost to recover use of more equipment.

Load curves are useful for generation planning and enable station engineers to study the pattern of variation of demand. They help to select size and number of generating units and to create operating schedule of the power plant.

2.2 Important definitions

To realize previous introduction, it is important to mention that load is divided into number of categories like private, public, Commercial, Entertainment, Hospitals, Transport, Industrial, Waterworks, and Street Light etc. After preparing the load sheet for a locality indicating the total load in each category (each category may have different types of loads such as light, fan, refrigerator, heater, pump etc) load curve is plotted for each category over a day (usually every hour or every 30 minutes) and then the final load curve for the locality is obtained by summing them. This is daily load curve for that locality as shown in the Figure (2-2), and following some basic definitions:

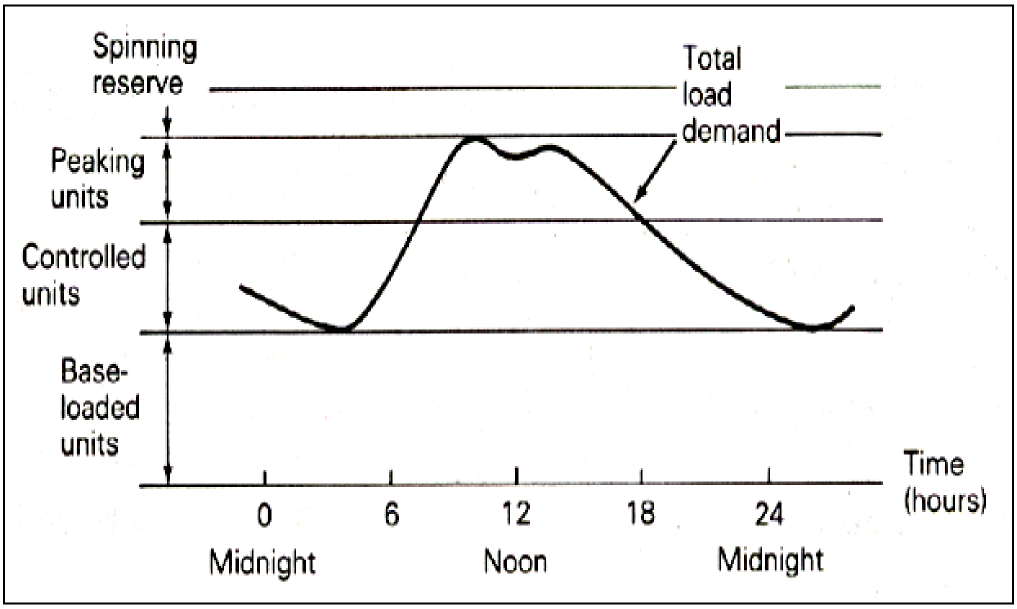


Figure 2-2: Daily load curve respect to range of demand.

Base load: The unvarying or minimum regular demands on the load curve.

Intermediate load: The area between minimum regular demands and beginning of peak loading and reduced when demand is low on the load curve.

Peak load: Various load peak demands on the load curve.

Maximum demand (MD): The greatest load demand on the power station during a given period or the highest peak on the power station load curve.

Demand Factor (DF): Ratio of maximum demand to connected load and this is usually less than one as shown below in equation (2.1).

$$\text{DF} = \frac{\text{Maximum Demand}}{\text{Connected Laod}} \tag{2.1}$$

Average load: This is the average of loads on the power station in a given period.

Daily average load: Average of loads on a power station in one day and it is equal to the total number of units multiply by generated power (KWHrs) over 24 Hrs.

Monthly average load: Average of loads on a power station in one month, and this is given in equation (2.2).

$$\text{MAL} = \frac{\sum \text{Unit} \times \text{Unit's Generated Power} \times 24\text{Hrs}}{\text{Number of Days} \times 24\text{ Hrs}} \tag{2.2}$$

Yearly average load: Average of loads on a power station in one year and it is equal to the total number of units over year hours (8760 Hrs)

Load factor (LF): The ratio of the average load to maximum demand and it is approximately equal or less than equal one as equation (2.3).

$$\text{LF} = \frac{\text{Average Load}}{\text{Maximum Demand}} \quad \text{or} \quad \text{LF} = \frac{\text{Annual Output}\left(\text{in KWHrs}\right)}{\text{Installed Capacity} \times 8760\text{ Hrs}} \tag{2.3}$$

This means that: High loading factor consequent with low cost per unit generated.

Diversity factor (DiF): The ratio of the sum of all individual maximum demands on the power station to the Maximum demand on the station. Consumer maximum demands do not occur at the same time thus maximum demand on power station will always be less than the sum of individual demands as equation (2.4).

$$\text{DiF} = \frac{\text{Individual Maximum Demand}}{\text{Total Station Maximum Demand}} \tag{2.4}$$

This mean that if high diversity factor (DiF) exist then we have low maximum demand (MD) and so low plant capacity with low investment capital required.

Plant capacity factor (PCF): The ratio of actual energy produced to the maximum possible energy that can be produced on a given period. This indicates the reserve capacity of a plant.

2.3 Load Curves

A load curve is a plot showing the variation of load with respect to time. Load curve of a locality indicates cyclic variation, as human activity in general is cyclic. This result in load curve of a day does not vary much from the previous day.

The following load curves are used in power stations:

Daily load curve: Load variations captured during the day (24 Hrs), recorded either half-hourly or hourly.

Monthly load curve: Load variations captured during the month at different times of the day plotted against No. of days.

Yearly load curve: Load variations captured during the Year, this is derived from monthly load curves of a particular year.

2.3.1 Information obtained by the load curves

- Area under load curve = Units generated
- Highest point of the curve = MD
- (Area under curve) ÷ (by total hours) = Average load
- (Area under load curve) ÷ (Area of rectangle containing load curve) = LF
- Helps to select size and number of generating units.
- Helps to create operating schedule of the power plant.

2.3.2 Selecting generating units

The following must be considered when selecting the generating units:

- Number and size of units to be approximately fit the annual load curve.
- Units to be of different capacities to meet load requirements.
- At least 15-20% of extra capacity for future expansion should be allowed for.
- Spare generating capacity must be allowed for to cater for repairs and overhauling of working units without affecting supply of minimum demand.
- Avoid selecting smaller units to closely fit load curve.

2.3.3 Meeting Load

The best method to meet load requirements on power station is to interconnect two different power stations in parallel as follows:

- More efficient plant as thermal and nuclear power stations carry the Base load
- Less efficient plant generally as Hydro, Pumped storage and gas turbine power stations carry peak load.

Careful study of load curves must be undertaken before deciding which type of station will be used for what purpose as this is greatly dependant on environmental issues and availability of fuel used by a particular power station.

CHAPTER 3
LITERATURE REVIEW AND SCOPE

3.1 Literature Review

The major number of power systems is mainly dependent on thermal power generation. Several operating strategies are possible to meet the required power demand, which varies from time to time over the day, and no one doubt that the size of any electric power system is in continuously increasing manner to meet the grown energy requirements. So, 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 it becomes necessary to operate the plant units most economically [5]. In other words, an important criterion in power system operation is to meet the power demand at minimum fuel cost using an optimal mix of different power plants. Moreover, in order to supply high quality electric power to customers in a secured and economic manner, thermal unit commitment is considered to be one of the best available options. It is thus recognized that the optimal unit commitment of thermal systems results in a great saving for electric utilities. Unit Commitment is the problem of determining the schedule of generating units within a power system subject to device and operating constraints. There have been several mathematical programming techniques proposed so far to solve the unit commitment problems. They include Priority List, Dynamic Programming, Branch and Bound, Lagrangian Relaxation, Simulated Annealing, Expert Systems, Artificial Neural Networks [2].

Fuzzy logic was discovered by Lotfi Zadeh in in 1965 at the University of California, Barkeley [6]. 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 explicitly known, or is difficult to solve. Furthermore, fuzzy logic is a technique, which approximates reasoning, while allowing decisions to be made efficiently [6, 7, 8]. In our work, to reach an optimal Unit Commitment schedule, incremental fuel cost, start-up cost, load capacity of each generator and production cost and are all expressed in fuzzy set notation and by [9] the qualitative interpretation of results using fuzzy logic appears to be attractive. So, the basic objective of the research 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 or maybe better compared to dynamic programming. In 1966, Kerr *et al.* [10] have elaborated the need of unit commitment in the power system for economic point of view, discussed various aspects of unit commitment and procedure to formulate the unit commitment problem and its solution.

Publications on the unit commitment field have been abundant over the last years. In the following is a summary of some different methods used in solving of the UC problem:

In 1966 also, Lowery [11] determined the feasibility of using dynamic programming to solve the generating unit commitment problem. Results of the study showed that simple, straight forward constraints are adequate to produce a usable optimum operating policy. Also, required computer time to produce a solution is small; hence, the method was feasible.

In 1971 Guy, [12] used a constrained search technique is used to determine which units to shut down or start up in future hours to minimize system fuel costs, including start-up costs. Results in a generating unit schedule which meets system reliability requirements and yields minimum fuel costs.

In 1985, Bosch *et al.* [13] proposes decomposition and dynamic programming as techniques for solving the unit commitment problem, a high dimensional non-linear, mixed-integer optimization problem. Experiments indicate that the proposed methods locate in less time a better solution than many existing techniques.

In 1987, Cohen *et al.* [14] described a new method which solves the unit commitment problem in the presence of fuel constraints. The method applied to a production-grade program suitable for Energy Management Systems applications.

In 1991, Hussain *et al.* [15] presented the limitations of the existing UC program against the various constraints are overcome by applying simple techniques rather than spending time and money on ordering special new software. This objective was difficult to achieve with the existing software, but, together with other requirements.

In 1991, Ouyang *et al.* [16] have presented a heuristic improvement of the truncated window dynamic programming technique was being studied for the unit commitment application. An iterative process for the number of strategies saved in every stage was also incorporated to fine tune the optimal solution.

In 1998, Mantawy et al. [17] have presented a Simulated Annealing Algorithm (SAA) to solve the Unit Commitment Problem (UCP). New rules for randomly generating feasible solutions are introduced. The problem has two sub problems: a combinatorial optimization problem and a nonlinear programming problem. The former is solved using the SAA while the latter problem is solved via a quadratic programming routine.

In 1998, Yang et al. [18] have proposed a constraint logic programming (CLP) algorithm to solve the thermal unit commitment (UC) problem. The results obtained compared with those from the established methods of the dynamic programming (DP), the Lagrangian relaxation (LR) as well as the simulated annealing (SA).

In 2004 et al. [19], Duraiswamy at el. have discussed the application of fuzzy logic to the unit commitment problem and showed a qualitative description of the behavior of a system and got the response without the need for exact mathematical formulations It was applied on a The Neyveli Thermal Power Station (NTPS) unit 11 in India and showed the effectiveness of the proposed approach that a fuzzy logic based approach which achieved a logical cost of operation of the system.

In 2005, Sriyanyong et al. [20] proposed Particle Swarm Optimization (PSO) combined with Lagrange Relaxation method (LR) for solving Unit Commitment (UC). The proposed approach employed PSO algorithm for optimal settings of Lagrange multipliers. The feasibility of the proposed method was demonstrated for 4 and 10unit systems, respectively.

3.2 Thesis Objective

The main objective of this thesis is to introduce a suggested method and to implement it to solve unit commitment problem based on Fuzzy Logic. In addition, the proposed technique aims to find a feasible and a logical optimum or near-optimal economical cost of operation of the given power system and to generalize this solution over other similar systems, which is the major objective of unit commitment. So, to minimize the total operating cost after determining good generation planning by taking into account a several constraints that are: power generation limits, operating within acceptable ramp rates, keeping adequate spinning reserve, and at the same time satisfying the power balance within the system. At the end, the results will be compared with the dynamic programming method to demonstrate the superiority of the implemented Fuzzy Logic Approach.

3.3 Research Methodology

In order to achieve these objectives, the following procedure will be carried out:

1. Choosing a suitable model to be dealt with which have realistic number of generating units, load profile over day and units characteristics
2. Formulating the problem of unit commitment as mathematical optimization problems subject to the applicable constraints.
3. Developing a MATLAB computer program capable of dealing with the formulated problem.
4. Tabulating the results obtained by the fuzzy logic based approach and comparing it with dynamic programming strategy.

3.4 Thesis Contribution

The main contribution of this work is to demonstrate that a Fuzzy Logic approach could be formulated mathematically and could be employed to be an effective alternative technique over dynamic programming which is the most famous method used for solving unit commitment problem. The fuzzy logic based approach attempts to find new combination of units that will be better than previous combinations got be dynamic programming. In addition, deal with different size systems and divide time zone over a day into more than six periods will be very useful to determine online generation units and get more reliable accurate results due to load variation over the hours of the day.

CHAPTER 4

THE UNIT COMMITMENT PROBLEM

4.1 Introduction

The unit commitment deals with the unit generation schedule in a power system for minimizing operating cost and satisfying main constraints such as load demand and units generation limits with a certain system reserve requirements over a set of time periods [1–20]. Since generators cannot instantly turn on and produce power, unit commitment (UC) must be planned in advance so that enough generation is always available to handle system demand with an adequate reserve margin in the event that generators or transmission lines go out or load demand increases. The classical UC problem is aimed at determining the start-up and shutdown schedules or ON/OFF states schedules of thermal power generation units to meet forecasted power demand over certain time periods and it belongs to a class of combinatorial optimization problems.

The main factor that controls the most desirable load allocation between various units is the running cost. So, fuel cost makes the major contribution to operating cost of power thermal plants. Fuel supplies for the thermal plants can be coal, natural gas, or nuclear fuel. The other costs such as cost of labor, 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 work is to find logical and feasible, optimum or near-optimal operational cost of the given power system, which is the major objective of unit commitment subjected to certain constraints will be mentioned later which are two kinds of constraints, quality and inequality ones [8].

4.2 The Unit Commitment Constraints

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 startup 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 [4]. Many constraints could be suitable to apply on the unit commitment problem. Where each of 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 as previous shown in chapter 2.

Spinning Reserve: is describes the total generation power available from turned on standby or quick started units to be on spinning state on the system. Spinning reserve also must follow 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. And in a simple manner, if one unit is lost by certain fault or suddenly load is exist, there must be enough reserve on the other units to make up for the loss in a specified time period.

Minimum up time: unit cannot be turned off immediately while it was running, so minimum needed time to turn off the unit called minimum up time.
Minimum down time: also there is a minimum time needed before the generating unit could be recommitted, so the minimum time needed to turn on the unit if it is in off or de-committed state called minimum down time.

In addition, a certain amount of energy must be expended to bring the unit online as the temperature and pressure of the thermal unit are required to move slowly, this energy does not result in any MW generation from the unit and is brought into the unit commitment problem as a “start-up cost.” [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 up to the operating temperature, in time for a scheduled turns 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 [1].
Startup cost when *cooling* is given by equation (4.1):

$$C_c\left(1-\varepsilon^{-t/\alpha}\right)\times F+C_f \qquad (4.1)$$

Where

C_c = cold-start cost (MBtu)

F = fuel cost

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

ε = thermal time constant for the unit

t= time (h) the unit was cooled

Start-up cost when *banking* is given by equation (4.2).

$$C_t \times t \times F + C_f \qquad (4.2)$$

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.

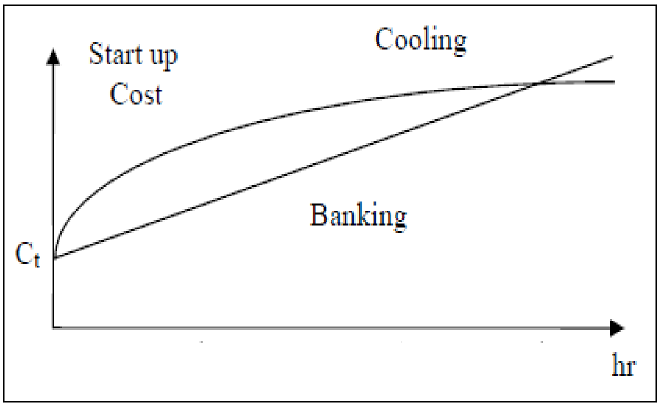


Figure 4-1: Time-dependent start-up costs.

Must run: where some units status are determined a must run during certain times of the year due to may reason such as voltage support on the transmission network or for such purposes as supply of steam for uses outside the steam plant itself or else.

Fuel constraint: when the plant has some units restricted by a limited fuel, or else have constraints that require them to burn a precise amount of fuel in a given time, present a most challenging in unit commitment problem [1, 13].

Hydro-constraints: which states that unit commitment cannot be completely separated from the planning of hydro-units and so, we could not expect that the result will be an optimal if the hydro thermal scheduling assumed to be separated from the UCP.

4.3 Fuel Cost Estimation

The knowledge of fuel cost in unit commitment problem is the main core to solve it, and it may be divided into two categories: Transitional cost and Production or Running cost. Generally production cost is the fuel cost required to meet the load demand. It depends on many determinants such as the unit loading, ramp or heat rate and fuel price. Transitional cost is the cost related with the transitions between periods of operations where we have starting of the unit and this part of cost may include both start-up and shutting down cost.

4.3.1 Production cost

As previously explained in section 4.3, the formula for the production cost could be written as following equation (4.3):

$$F_i\left(P_i\right) = a_i P_i^2 + b_i P_i + c_i \tag{4.3}$$

Where $P_{i,t}$ is the Power generation (in MW) of unit i , at hour t and a_i , b_i , c_i are the running fuel cost coefficients. The production cost is the cost of the fuel required by a given set of running power generating units to meet the load demand in specified power system network. Since the essential objective of the unit commitment problem is to minimize the overall cost, the production cost should also get minimized as well.

Several methods of economic dispatch are available to determine the minimal production cost such as iterative or direct search techniques. As compared to the number of economic dispatches that would be performed, a simple, feasible and fast economic dispatch procedure will be chosen as quadratic programming. And to achieve this job, the units are assumed to have quadratic 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 the generation range capability. It is also taken care that the various spinning reserve requirements described above are not violated. The dispatch which satisfies all mentioned constraints is considered as an economical and feasible one. And by the described technique in dispatching, an economic and feasible solution 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 pre-specified priority in order to reduce the dispatching effort [4, 10].

4.3.2 Transitional Cost

The observer could note that shutting down of units maybe not associated with cost because usually the cost controlled by running cost coefficients. But to be more realistic, shutdown costs must be included in the computation of total cost and this transitional cost make the problem of unit commitment more difficult to solve, since if it doesn't contain ant transitions between period, it will be only one optimization process of a cost function per each period. Assumption was taken which is constant cost may be specified for each unit as the shutdown cost and this cost is taken to be independent of the time; the state of unit has been on-line or running before the shutdown occurred.

Usually some form of startup cost is considered in transitions. A simple practice is to assume a constant cost not related with the unit down time. So, in order to get a more accurate measure of the actual cost involved, a time dependent startup cost is required. The startup cost is expected to be dependent on the temperature of the unit considered and so on it’s down time. Since the cooling rate of a unit is approximately exponential, an exponential startup cost curve is generally accepted though other forms of unit cost curve may also be used [1]. 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 [9].

4.4 Formulation of the Unit Commitment

After the previous explanation of unit commitment problem we could now describe it mathematically through the following equation (4.4):

$$\text{Min } F_i\left(P_i^t,\ U_i^t\right) = \sum_t \sum_i [(a_i P_i^2 + b_i P_i + c_i) + SC_i^t (1 - U_i^{t-1})] U_i^t \tag{4.4}$$

Where $F_i(P_i^t)$ is generator fuel cost function in quadratic form, a_i , b_i and c_i are the running cost coefficients of unit i, and P_i^t is the power generation of the same unit at time t, and the overall objective is to minimize subject to a number of system and unit constraints. All the generators are assumed to be connected to the same bus supplying the total system demand. Therefore, the networks constraints are studied above are as follows briefly:

4.4.1 Power Balance Constraints

To satisfy the load balance in each stage, the forecasted load demand should be equal to the total power generated for every feasible combination. Equation (4.5) represents this constraint where P_D^t represents the total power load demand at a certain period.

$$\sum_{i=1}^{N} P_i^t U_i^t - \left(P_D^t\right) = 0 \tag{4.5}$$

4.4.2 The period of spinning reserve

Reserve requirements **R** which must be met and this could be formulated as in equation (4.6):

$$\sum_{i=1}^{N} P_i^{max} U_i - \left(P_D\right) = R \qquad t = 1, 2, 3 \ldots.T \tag{4.6}$$

4.4.3 Generation Limits

Each unit must satisfy the generation range and this certain rated range must not be violated. This can be accomplished through satisfying the equation (4.7):

$$P_i^{min} U_i^t \leq P_i \leq P_i^{max} U_i^t \qquad i = 1, 2, 3 \ldots. N \tag{4.7}$$

Where: P_i^{min} and P_i^{max} are the generation limits of unit i.

4.4.4 Ramp-Up and Ramp-Down Constraints

To avoid damaging the turbine, the electrical output of a unit cannot be changed by more than a certain amount over a period of time. For each unit, the output is limited by ramp up/down rate at each hour as equations (4.8) and (4.9):

$$P_i^{t-1} - P_i^t \leq RD_i \qquad \text{if } (U_i^t = 1) \text{ and } (U_i^{t-1} = 1) \tag{4.8}$$

$$P_i^t - P_i^{t-1} \leq RU_i \qquad \text{if } (U_i^t = 1) \text{ and } (U_i^{t-1} = 1) \tag{4.9}$$

Where: RD_i and RU_i are respectively the ramp down and ramp up rate limit of unit i.

4.5 Solving Economic Dispatch by Equal Incremental Cost Criteria

The basic economic dispatch problem could be described mathematically as a minimization problem by equation (4.10):

$$\text{Minimize} \sum_{i=1}^{n} F_i(P_i) \tag{4.10}$$

Where $F_i(P_i)$ is the fuel cost equation of the i[th] plant, it is the variation of fuel cost ($) with generated power (MW). Normally it is expressed as quadratic form as equation (4.11):

$$F_i\left(P_i\right) = a_i P_i^2 + b_i P_i + c_i \tag{4.11}$$

If $a_i \geq 0$ then the quadratic fuel cost function is monotonic. The total fuel cost is to be minimized subject to the following constraints, the first one shown in equation (4.12).

$$\sum_{i=1}^{n} P_i = D \tag{4.12}$$

By lagrangian multipliers method and Kuhn tucker conditions and the following equations (4.13) and (4.14) show the conditions for optimality can be obtained:

$$2a_i P_i + b_i = \lambda \qquad i = 1, 2, 3, \ldots\ldots, n \tag{4.13}$$

$$P_i^{min} U_i^t \leq P_i \leq P_i^{max} U_i^t \qquad i = 1, 2, 3, \ldots\ldots, n \tag{4.14}$$

The nonlinear equations and inequalities are solved by the following procedure:

Initialize the procedure by allocate the lower generation limit of each plant as shown equation (4.15)

$$P_i = P_i^{min} \tag{4.15}$$

Use QP to determine allocation.

Check for convergence by equation (4.16)

$$\left| \sum_{i=1}^{n} P_i \text{-} D \right| \leq \varepsilon \tag{4.16}$$

Carry out the steps 2 and 3 till convergence.

Quadratic Programming is an effective optimization method to find the global solution if the objective functions is quadratic and the constraints are linear.

To prepare economic dispatch problem we should put it in QP standard form:

Minimize: $X.H.X^T + f^T.X$

Subject to: $KX \leq B$, $X^{min} \leq X \leq X^{max}$

$X = [x_1, x_2, x_3, \ldots\ldots x_n]^T$, $f = [f_1, f_2, f_3, \ldots\ldots f_n]^T$, $B = [B_1, B_2, B_3, \ldots\ldots B_n]^T$

Where H is a Hessian matrix of size $n \times n$, K and B is $m \times n$ matrices representing inequality constraints.

To solve the economic dispatch via Quadratic Programming technique, we must define basic four matrices that are: H, f, K and B

Where:

$H = \text{diag}\left([a_1, a_2, a_{3,} \ldots\ldots a_n]\right)$, $f = ([b_1, b_2, b_3, \ldots\ldots b_n]^T)$, $K = \left[1,1,\ldots\ldots,1\right]$ $1 \times n$ matrix

And $B = [B_1, B_2, B_3, \ldots\ldots B_n]^T = [D_1, D_2, D_3, \ldots\ldots D_n]^T$ equal to the demand matrix

Here, after explaining QP procedure we note that we use it to determine power allocation of each unit to get the best dispatch as in the third step for economic dispatch solution by equal incremental cost criterion [29].

4.6 Solution Methods for the Unit Commitment

Here we introduce some major techniques used in solving the unit commitment problem such as the exhaustive enumeration, priority method, dynamic programming, mixed integer programming and the Lagrange relaxation method.

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 search* and *mathematical programming methods*. Below some used techniques in solving unit commitment problem.

4.6.1 Exhaustive Enumeration

The UC problem may be solved by enumerating all possible combinations of the generating units. Once this process is complete, the combination that yields the least cost of operation is chosen as the optimal solution. This method finds the optimal solution once all the system constraints and conditions are considered.

4.6.2 Priority-List Methods

This method arranges the generating units in a start-up heuristic ordering by operating cost combined with transition costs. The pre-determined order is then used to commit the units such that the system load is satisfied. Variations on this technique dynamically rank the units sequentially. The ranking process is based on specific guidelines. The Commitment Utilization Factor (CUF) and the classical economic index Average Full-Load Cost (AFLC) can also be combined to determine the priority commitment order.

Priority list will give theoretically correct dispatch and commitment results using arranged full load average cost rate in order only if the following conditions are being satisfied:

- Zero "no load" costs.
- Start-up costs have a fixed amount.
- Unit input-output characteristics are linear between zero output and full load.
- No other restrictions take into account.

4.6.3 Dynamic Programming Techniques

The DP method is flexible, but the disadvantage is the “curse of dimensionality” which results in more mathematical complexity and increase in computation time, if the constraints are taken into consideration [1]. Solution is being developed from the sub-problems respectively by decomposing a problem into a series of smaller problems, and solves them individually to achieve an optimal solution to the basic problem step-by-step. So it examines every possible state in every interval. Some of these states are found to be infeasible and hence they are rejected instantly.

Suppose a system has n units. If the enumeration approach is used, there would be $2^N - 1$ as maximum number of combinations. The dynamic programming (DP) method consists in implicitly enumerating feasible schedule alternatives and comparing them in terms of operating costs. Thus DP has many advantages over the enumeration method, such as reduction in the dimensionality of the problem. There are two DP algorithms. They are *forward dynamic programming* and *backward dynamic programming*. The forward approach, which runs forward in time from the initial hour to the final hour, is often adopted in the unit commitment. The advantages of the forward approach are:

- Generally, the initial state and conditions are known.
- The start - up cost of a unit is a function of the time. Thus the forward approach is more suitable since the previous history of the unit can be computed at each stage.

Forward approach: The problem is broken into sub problems, and these sub problems are solved and the solutions remembered, in case they need to be solved again. This is recursion and memorization combined together.

Backward approach: All sub problems that might be needed are solved in advance and then used to build up solutions to larger problems. This approach is slightly better in stack space and number of function calls, but it is sometimes not intuitive to figure out all the sub problems needed for solving the given problem

In the dynamic programming which is familiar approach we assumed that:

1. Each period contains of two groups of units which are on-line units and rest off-line others.
2. Fixed start-up cost for all units (independent of the time).
3. Zero shutting down cost for all units.
4. A specified amount of generated power must be exist in each period, and this strict us by priority order.

4.6.4 Mixed integer programming (MIP)

The Mixed-Integer Programming (MIP) approach solves the UC problem by reducing the solution search space systematically through discarding the infeasible subsets. Dual programming is also suggested for the solution of the thermal UC problem. The general solution concept is based on solving a linear program and checking for an integer solution. If the solution is not integer, linear problems or sub problems are continuously solved. The problems are not similar because the number and type of integer variables are changed while holding the variables at a fixed integer value. Branching is the strategy adopted to determine which variables to hold constant.

4.6.5 Lagrange Relaxation Method

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 offline during period t

U_i^t = 1 if unit (*i)* is online during period t

Objective function of the unit commitment problem and related constraints as follows:

The objective function is shown in equation (4.17):

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\left[F_i\left(P_i^t\right)+\text{startup cost}_{i,t}\right]U_i^t=F\left(P_i^t,U_i^t\right) \tag{4.17}$$

Loading Constraints are shown by equation (4.18):

$$\sum_{i=1}^{N} P_i^t U_i^t-\left(P_D^t\right)=0 \tag{4.18}$$

Unit Limitations are considered by equations (4.19)

$$P_i^{min}U_i^t \leq P_i \leq P_i^{max}U_i^t \qquad i = 1, 2, 3 \;.... \quad N \tag{4.19}$$

Then, the Lagrange function obtained from equation (4.20):

$$L\left(P,U,\lambda\right)=F\left(P_i^t,\,U_i^t\right)+\sum_{t=1}^{T}\lambda^t\,(P_{load}^t-\sum_{i=1}^{N}P_i^tU_i^t\;) \tag{4.20}$$

Lagrange Relaxation technique can be easily modified to model characteristics of specific utilities, it can deal with different types of constraints very flexibly and it is relatively easy to add constraints, also it incorporates even those additional coupling constraints that have not been considered so far, very easily. Lagrangian relaxation method is also more flexible than dynamic programming because no priority ordering is imposed. It is computationally much more attractive for large systems. But in the other hand lagrangian relaxation has a weakness is that the optimal solution rarely satisfies the once relaxed coupling constraints, and 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.

CHAPTER 5
FUZZY LOGIC APPROACH AND APPLICATION

5.1 Introduction

The aim of unit commitment or economic scheduling of generator is to guarantee the optimum combination of generators connected to the system to supply the load demand. The unit commitment involves the selection of units that will supply the expected load of the system at minimum cost over a required interval of time as well as provide a specified margin of the operating reserve, known as the spinning reserve with determination of load distribution 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.

5.2 Fuzzy System

The dictionary meaning of the word "fuzzy" is "not clear". By contrast, in the technical sense, fuzzy systems are precisely defined systems, and fuzzy control is a precisely defined method of non-linear control. The main goal of fuzzy logic is to mimic (and improve on) "human-like" reasoning. "Fuzzy systems are knowledge-based or rule-based systems" [22], specifically, the key components of fuzzy system's knowledge base are a set of IF-THEN rules obtained from human knowledge and expertise. The fuzzy systems are multi-input-multi-output mappings from a real-valued vector to a real-valued scalar.

5.2.1 Why Fuzzy?

Natural language is one of the most powerful forms of conveying information. The conventional mathematical methods have not fully tapped this potential of language. According to Timothy J. Ross [23], "scientists have said, the human thinking process is based primarily on conceptual patterns and mental images rather than on numerical quantities". So if the problem of making computers with the ability to solve complex issues has to be solved, the human thought process has to be modeled. The best way to do this is to use models that attempt to emulate the natural language; the advent of fuzzy logic has put this power to proper use. Most if not all of the physical processes are non-linear and to model them, a reasonable amount of approximation is necessary.

For simple systems, mathematical expressions give precise descriptions of the system behavior.

For more complicated systems with significant amounts of data available, model-free methods provide robust methods to reduce ambiguity and uncertainty in the system. But for complex systems where not much numerical data exists, fuzzy reasoning furnishes a way to understand the system behavior by relying on approximate input-output approaches. The underlying strength of fuzzy logic is that it makes use of linguistic variables rather than numerical variables to represent imprecise data.

5.2.2 Fuzzy Sets

The key difference between classical sets and fuzzy sets is that in the former, the transition for an element in the universe between membership and non-membership in a given set is well defined, that is the element either belongs or does not belong to the set. By contrast, for elements in fuzzy sets, the membership can be a gradual one, allowing for the boundaries for fuzzy sets to be vague and ambiguous.

5.2.3 Membership Function

A fuzzy set is characterized by a membership function whose value ranges from zero to one. It consists of members with varying degrees of membership based on the values of the membership function. In mathematical terms, the fuzzy set A in the universe U can be represented as a set of ordered pairs of an element x and its membership function $\mu_A(x)$. Formally we have:

$A = \{(x, \mu A(x)) \mid x \in U, \text{ where U is continuous}\}$

For more detailed description of fuzzy sets and the set operations that can be performed on them, see references [22] and [23]. A membership function is a continuous function in the range of 0 to 1. It is usually decided from human expertise and observations made and it can be either linear or nonlinear. Its choice is critical for the performance of the fuzzy logic system since it determines all the information contained in a fuzzy set. In the voltage and reactive power control problems under study in this research, the membership functions will help in automating the fuzzy control. The rules were framed through numerous simulations, which are carried out to determine the best possible set of rules aimed at pushing the stability limits of the system to its maximum. The membership functions can be estimated by studying the behavior of different conditions and for different contingency cases. They should be able to accommodate all the non-linearities of the system, making their determination a complex task.

5.2.4 Fuzzy Rule Base – IF-THEN Rules

Fuzzy logic has been centered on the point that it makes use of linguistic variables as its rule base. *Li-Xin Wang* [24] said that *"If a variable can take words in natural language as its values, it is called linguistic variable, where the words are characterized by fuzzy sets defined in the universe of discourse in which the variable is defined"*. Examples of these linguistic variables are slow, medium, high, young and thin. There could be a combination of these variables too, i.e. "slow-young horse", "a thin young female". These characteristics are termed atomic terms while their combinations are called compounded terms. In real world, words are often used to describe characteristics rather than numerical values. For example, one would say "the car was going very fast" rather than say "the car was going at 100 miles per hour". Terms such as slightly, very, more or less, etc. are called linguistic hedges since they add extra description to the variables, i.e. very-slow, more or less red, slightly high.

5.2.5 Mamdani Inference Systems Method

There are a lot of inference methods which deals with fuzzy inference such as Mamdani method, Larsen method, Tsukamoto method and Sugeno style inference. The widely and most important used method in fuzzy logic is the Mamdani method.

This fuzzy inference method is the most commonly used. In 1974, Professor Ebrahim Mamdani of London University built one of the first fuzzy systems to control a steam engine and boiler combination. He applied a set of fuzzy rules supplied by experienced human operators [8]. The Mamdani style fuzzy inference process is performed in four steps:

- Fuzzification of the input variable.
- Rule evaluation.
- Aggregation of the rule output.
- Defuzzification.

The system shown in Figure 5-1 incorporates all the essential features of fuzzy systems. To illustrate the fuzzy inference, each step will be explained in more details.

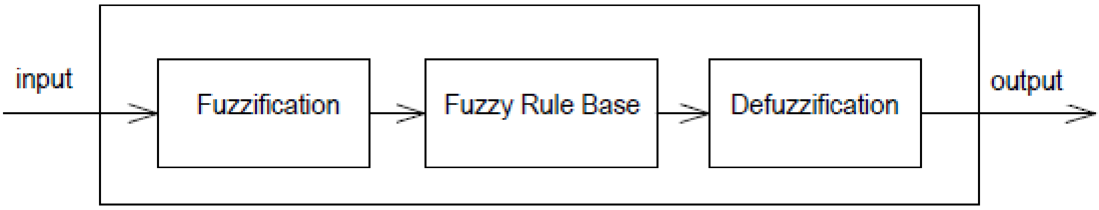


Figure 5-1: Configuration of a fuzzy system with fuzzifier and defuzzifier

Step 1: Fuzzification

The fuzzifier is a mapping from the real valued point, $x^* \in U$ to a corresponding fuzzy set $A' \subset U$, which is the input to the fuzzy inference engine. The fuzzifier needs to account for certain criteria while performing this mapping. The first of these criteria states that the input is a crisp point (x^*) so that its mapping in U is a fuzzy set A′ that has a large membership value. The second criterion states that the fuzzifier must be able to suppress the noise inherent in real valued inputs. The third criterion is that the fuzzifier must be able to simplify the computations in the fuzzy inference engine. Three types of fuzzifiers have been proposed by Li-Xin Wang [24], which are singleton, Gaussian, and triangular fuzzifiers. They are defined as follows:

Singleton Fuzzifier: This maps a real valued point $(x^* \in U)$, with a membership function $\mu_{A'}$(x) into a fuzzy singleton ($A' \subset U$). Specifically we have formula (5.1)

$$\mu_{A'}(x) = \begin{cases} 1 & \text{if } x = x' \\ 0 & \text{otherwise} \end{cases} \quad (5.1)$$

Gaussian Fuzzifier: This maps a real valued point $x^* \in U$ into a fuzzy set $A' \subset U$ with a membership function given by equation (5.2)

$$\mu_{A'}(x) = e^{-\left(\frac{x_1 - x_1^*}{a_1}\right)^2}, e^{-\left(\frac{x_2 - x_2^*}{a_2}\right)^2},,,,,, e^{-\left(\frac{x_n - x_n^*}{a_n}\right)^2} \quad (5.2)$$

Where: $\{a_i , i = 1,2,3 \ldots \ldots \ldots\ n\}$ *are positive parameters*

Triangular Fuzzifier: This maps a real valued point $(x^* \in U)$, into a fuzzy set $A' \subset U$ with a membership function written as equation (5.3)

$$\mu_{A'}(x) = \begin{cases} \left(1 - \frac{|x_1 - x_1^*|}{b_1}\right) \ldots \left(1 - \frac{|x_n - x_n^*|}{b_n}\right) & if\ |x_i - x_i^*| \le b_i \\ 0 & otherwise \end{cases} \quad (5.3)$$

Where: $\{b_i, i = 1,2,3 \dots \dots \dots\ n\}$ $are\ positive\ parameters$

Note that all these fuzzifiers satisfy the first criterion as mentioned above, that is to say they have a large membership value at the input point. It can be observed that the singleton fuzzifier simplifies the computations involved in the fuzzy inference engine for any type of membership functions, while the other two fuzzifiers simplify the computations if the membership is either Gaussian or triangular, respectively. On the other hand, the Gaussian and triangular fuzzifiers can suppress noise while the singleton fuzzifier can't.

Step 2: Rule Evaluation

The second step is to take the fuzzified inputs, and apply them to the antecedents of the fuzzy rules. If a given fuzzy rule has multiple antecedents, the fuzzy operator (*AND* or *OR*) is used to obtain a single number that represent the result of the antecedent evaluation.

Step 3: Aggregation of the Rule Output

Aggregation is the process of unification of the outputs of all rules; we take the membership functions of rule consequents and combine them into a single fuzzy set.

Step 4: Defuzzification

The defuzzifier's task is the reverse operation to the fuzzifier. It maps the fuzzy output set, $B' \subset V$, from the fuzzy inference engine to a real valued point (crisp point), $y^* \in V$. In other words, it can be said that the defuzzifier gives the real point that best describes the fuzzy set B'. Naturally, there exist many choices for choosing this point, but the most suitable point can be determined by considering certain criteria. The point y^* should represent B' from an intuitive point of view; for example it should exhibit a high membership in B'. Furthermore, the defuzzifier has to have computational simplicity; this is particularly important because most of the fuzzy controllers are usually used in real time. Lastly, the defuzzifier must have continuity.

Centroid Defuzzifier: The centroid defuzzifier specifies the crisp point y^* as the center of the area covered by the membership function of (B'). If the membership function is viewed as a probability density function of a random variable, the Centroid defuzzifier gives its mean value. One inherent disadvantage of this method is that it is computational intensive.

Center Average Defuzzifier: The center average defuzzifier takes the weighted averages of all the fuzzy sets that are output from the inference engine, where the weight of each set is based on the height of that particular set to determine the point (y^*). This is a good approximation since the fuzzy set B' is either a union or an intersection of the inference engine's output. This is the most commonly used defuzzifier in fuzzy systems because of it computational simplicity and intuitive plausibility.

Maximum Defuzzifier: The maximum defuzzifier chooses y^* as the point at which the associated membership function achieves its maximum value. If more than one point satisfies this condition, then the maximum, or minimum, or mean of all such points is taken. While this type of defuzzifier is computationally simple and intuitively plausible, it lacks continuity wherein a small change in B' results in a large change in y^*

5.3 Fuzzy Logic Implementation

Fuzzy logic provides not only a meaningful and powerful representation for measurement of uncertainties but also a meaningful representation of blurred concept expressed in normally language. Fuzzy logic is a mathematical theory, which encompasses the idea of vagueness when defining a concept or a meaning. For example, there is uncertainty or fuzziness in expressions like \`large\` or \`small\`, since these expressions are imprecise and relative. Variables considered thus are termed \`fuzzy\` as opposed to \`crisp\`. Fuzziness is simply one means of describing uncertainty. Such ideas are readily applicable to the unit commitment problem.

5.3.1 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 the UCP are load capacity of generator (LCG), incremental fuel cost (IC), start-up cost (SUC) as an input variables and production cost (PRC) as output variable. Below we present briefly explaining of mentioned fuzzy variables:

- *The load capacity of generator* is considered to be fuzzy, as it is based upon the load to be served.
- *Incremental fuel cost* is taken to be fuzzy, because the cost of fuel may change over the period of time, and because the cost of fuel for each unit may be different.
- *Start –up costs* of the units are assumed to be fuzzy, because some units will be online and others will be offline. And it is important to mention that we include the start costs, shut costs, maintenance costs and crew expenses of each unit as a fixed value that is start-up cost. So, start-up cost of a unit is independent of the time it has been off line (it is a fixed amount).
- *Production cost* of the system is treated as a fuzzy variable since it is directly proportional to the hourly load.

Also, uncertainty in fuzzy logic is a measure of no specificity 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 in linguistically describing the physical process variables.

5.3.2 Fuzzy Set Associated with Unit Commitment

After identifying the fuzzy variables associated with unit commitment, the fuzzy sets defining these variables are selected and 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 capacity of the generator are [19]:

LCG = {Low, Below Average, Average, Above Average, High}

The incremental cost is stated by the following sets:
IC = {Low, Medium, Large}

The sets representing the start-up cost are formulated as follows:
SUC = {Zero, Small, Large}

The production cost chosen as the objective function is given by:
PRC= {Low, Below Average, Average, Above Average, High}

Based on the aforementioned fuzzy sets, the membership functions are chosen for each fuzzy input and output variable as shown in Figure 5-2. For simplicity, 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 as described next.

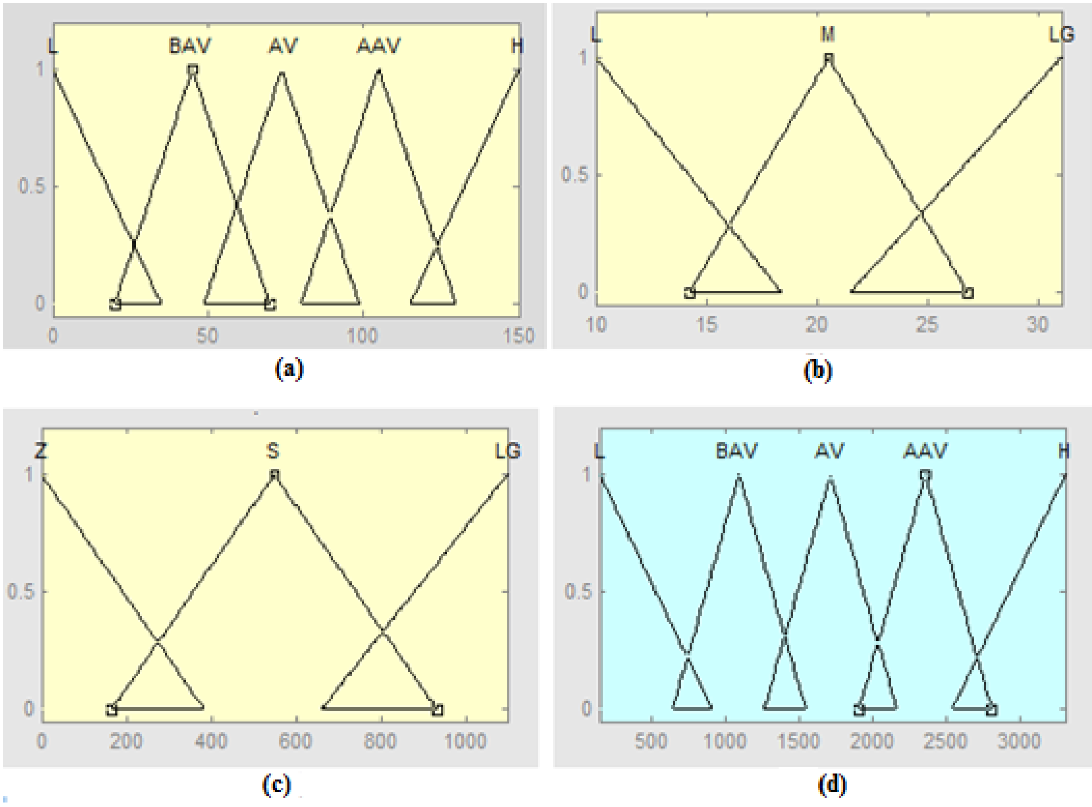


Figure 5-2: Membership function of input output variables
a) LCG membership, b) IC membership, c) SUC membership, d) PRC membership

5.3.3 Fuzzy If–Then Rules

If fuzzy logic based approach decisions are made by forming a series of rules that relate the input variables to the output variable using If–Then statements. Each rule in general can be represented in this manner: *If (condition) Then (consequence)*

Note that Load capacity of generator, incremental fuel cost, and start–up cost are considered as input variables and production cost is treated as the output variable. This relation between the input variables and the output variable is given as:

Production cost =

{Load capacity of generator} **AND** {Incremental fuel cost} **AND** {Start–up cost}

In fuzzy set notation this is written as, $\mathrm{PRC} = \mathrm{LCG} \cap \mathrm{IFC} \cap \mathrm{SUC}$

Hence, the membership function of the production cost, μ PRC is computed as:

$$\mu\text{PRC} = \mu\text{LCG} \cap \mu\text{IFC} \cap \mu\text{SUC}$$

Where μ LCG, μ IC and μ SUC are memberships of load capacity of generator, incremental fuel cost and start–up cost, and by using the above notation, fuzzy rules are written to associate fuzzy input variables with the fuzzy output variable. Based upon these relationships, and with reference to above figures, total sum of rules are 45 that could be composed because there are five subsets for *load capacity of generator*, three subsets for *incremental cost* and three subsets for *start–up cost* (5 × 3 × 3 = 45) . Here rule 7 as an example that can be written as follows:

Rule 7: IF (load capacity of generator is low, **AND** incremental fuel cost is large **AND** start–up cost is zero), **THEN** production cost is low.

5.3.4 Defuzzification Process

Defuzzification is the transformation of the fuzzy signals back to crisp values. One of the most commonly used methods of defuzzification is the **Centroid** or center of gravity method. Using this method, the production cost is obtained as formula (5.4):

$$\text{Production Cost} = \frac{\sum_{i=1}^{n} \mu(PRC)_i \times PRC_i}{\sum_{i=1}^{n} \mu(PRC)_i} \tag{5.4}$$

Where $\mu(PRC)_i$ is the membership value of the clipped output and $(PRC)_i$ is the quantitative value of the clipped output where n is the number of the points corresponding to quantitative value of the output.

So, the fuzzy results must be defuzzified by a certain defuzzification method after relating the input variable to the output variable as in Table 5-1. That is called a defuzzification process to achieve crisp numerical values.

Table (5-1): Used Fuzzy Rules That Relates Input / Output Fuzzy Variables

Rule	LCG	IC	SUC	PRC	Rule	LCG	IC	SUC	PRC
1	L	L	Z	L	24	AV	M	LG	AV
2	L	L	S	L	25	AV	LG	Z	AV
3	L	L	LG	L	26	AV	LG	S	AV
4	L	M	Z	L	27	AV	LG	LG	AV
5	L	M	S	L	28	AAV	L	Z	AAV
6	L	M	LG	L	29	AAV	L	S	AAV
7	L	LG	Z	L	30	AAV	L	LG	AAV
8	L	LG	S	L	31	AAV	M	Z	AAV
9	L	LG	LG	L	32	AAV	M	S	AAV
10	BAV	L	Z	BAV	33	AAV	M	LG	AAV
11	BAV	L	S	BAV	34	AAV	LG	Z	AAV
12	BAV	L	LG	BAV	35	AAV	LG	S	AAV
13	BAV	M	Z	BAV	36	AAV	LG	LG	AAV
14	BAV	M	S	BAV	37	H	L	Z	H
15	BAV	M	LG	BAV	38	H	L	S	H
16	BAV	LG	Z	BAV	39	H	L	LG	H
17	BAV	LG	S	BAV	40	H	M	Z	H
18	BAV	LG	LG	BAV	41	H	M	S	H
19	AV	L	Z	AV	42	H	M	LG	H
20	AV	L	S	AV	43	H	LG	Z	H
21	AV	L	LG	AV	44	H	LG	S	H
22	AV	M	Z	AV	45	H	LG	LG	H
23	AV	M	S	AV					

5.3 Algorithm of Dynamic Fuzzy Programming

In solving the UCP, two types of variables, first one are units states at each period $U_{i,t}$ which are integer or binary (0–1) variables, and second are the units output power variables P_i^t, which are continuous variables need to be determined. This problem can be considered into two sub-problems: the first is combinatorial optimization problem in **U**, while the other is a non–linear one in **P**.

First applied method to solve the UCP is Dynamic Fuzzy Programming that implemented to solve this complicated optimization problem. The economic dispatch is simultaneously solved via a quadratic programming routine. Figure 5-3 shows the flowchart of the proposed algorithm and major steps of the algorithm are:

Firstly: read units coefficients and load demand per period, then identify fuzzy input and output variables, then relate fuzzy input and output variables using fuzzy rules (If-then), determine feasible combinations of units considering given constrains and solve economic dispatch for these feasible combinations, and so repeat for all periods to get the minimum total production cost strategy, then finally getting ready stored variables which are LCG, IC, and SUP to defuzzify for the output variable (production cost).

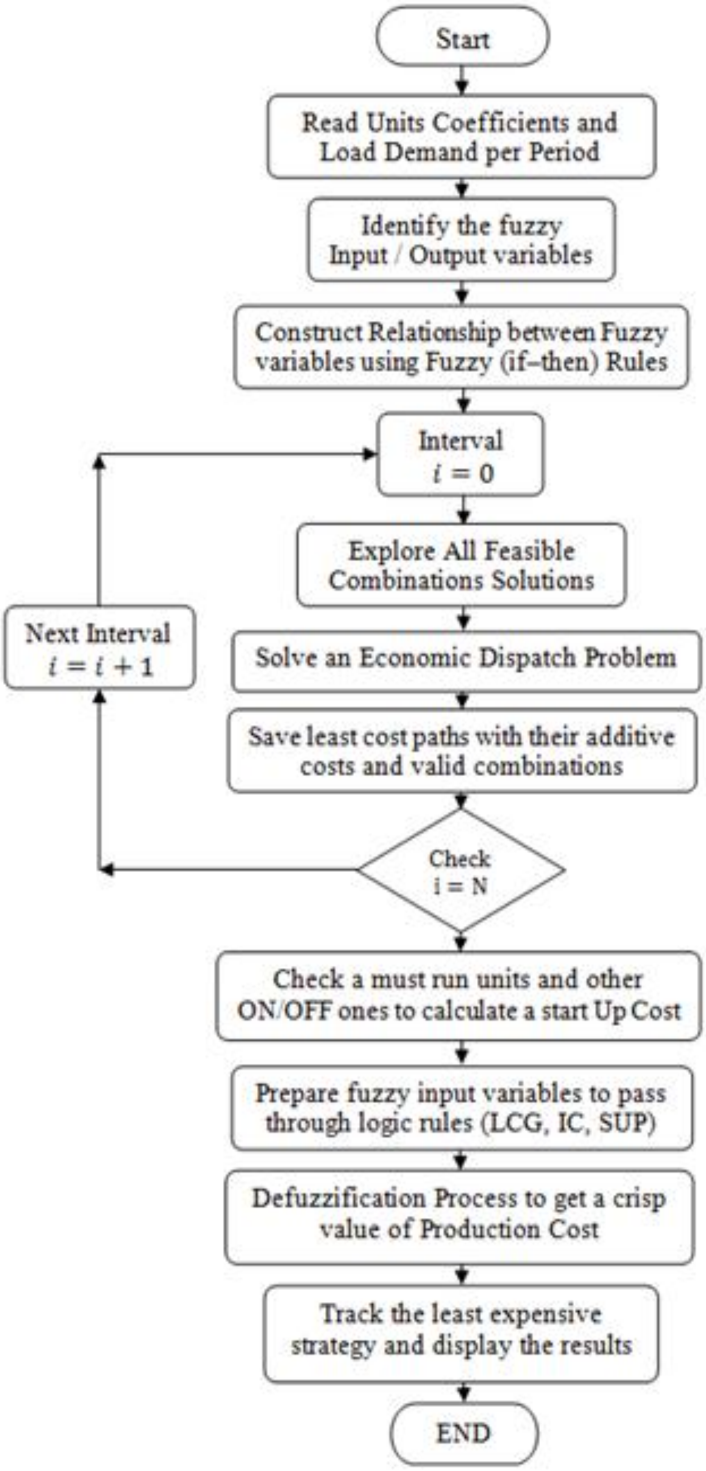


Figure 5-3: Flow chart of the Fuzzy Dynamic Programming Algorithm

5.4 Algorithm of Fuzzy Logic Based Approach

Second applied method to solve the UCP is the Fuzzy Logic Based Approach that is not much more differ from Fuzzy Dynamic Programming till it gives an alternative unit combinations and so different total production cost, that is due to bringing defuzzification process forward to inside check loop, so the result will be consisted of dynamic programming combination and fuzzy logic based combinations. Figure (5-4) shows the flowchart of the algorithm of the demonstrated approach:

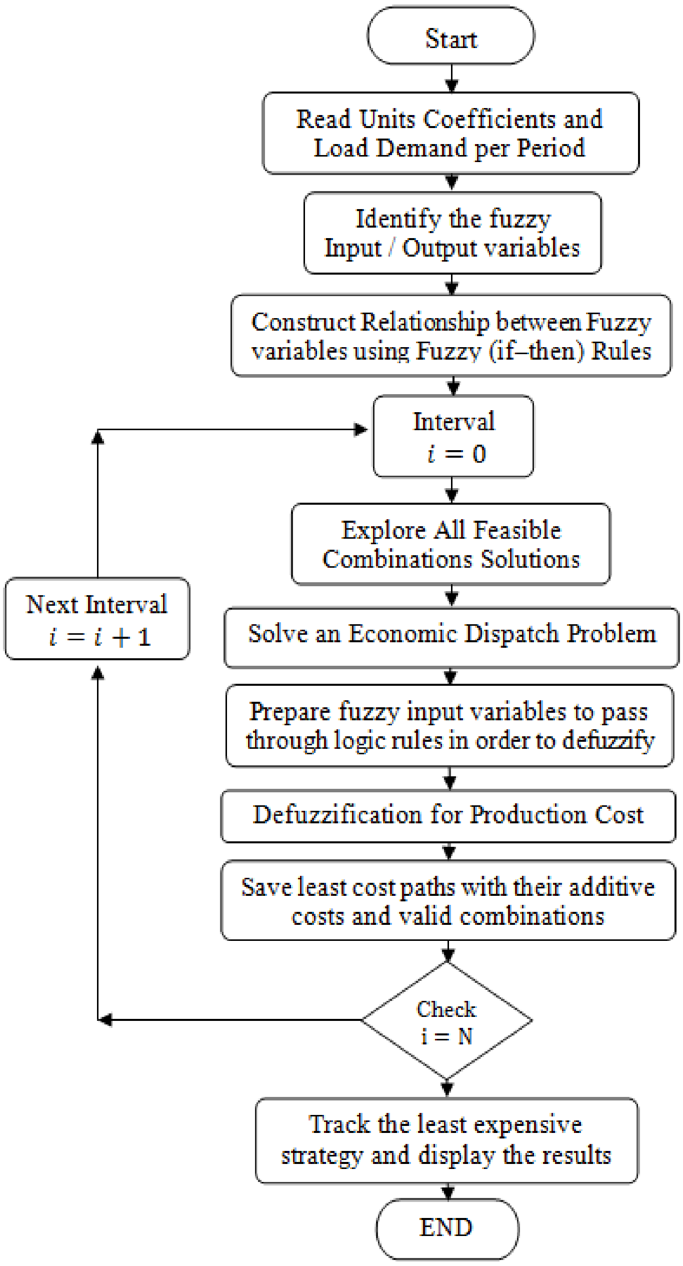


Figure 5-4: Flow chart of the Fuzzy Logic Based Approach

5.6 Four-Generating-Units Model

The Tuncbilek thermal power plant in Turkey with four generating units has been considered as a case study. A daily load demand divided into eight periods is considered. Table 5-2 contains this load demand [29] while Figure 5–5 graphs this demand. The unit commitment problem will be solved applying the dynamic programming and fuzzy logic approaches and the results will be compared.

Table 5-2: Daily Load demand

Stage	Demand (MW)
1	168
2	150
3	260
4	275
5	313
6	347
7	308
8	231

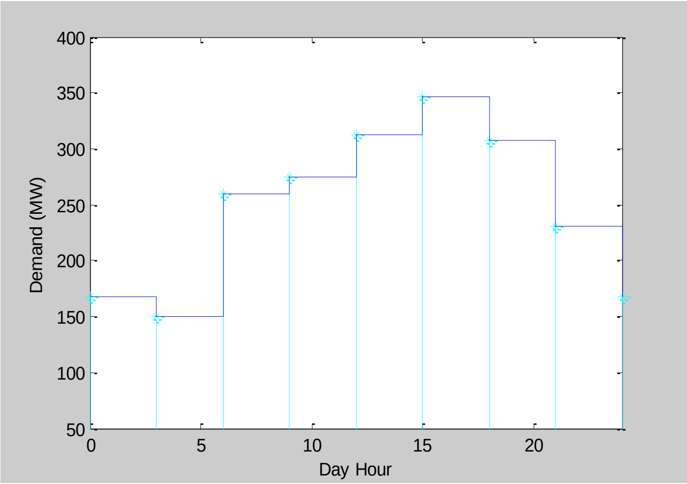


Figure 5-5: Daily Load demand over eight intervals

The characteristics of these four generating units including cost coefficients, maximum and minimum real power generation, start-up cost, and ramp rates of each unit of the Tuncbilek power plant are given in Table 5-3.

Table 5-3: Unit characteristics for the four-unit Tuncbilek thermal power plant

Unit No.	Generation Limits		Running Cost			Start-up Cost	
	Pmin (MW)	Pmax (MW)	a ($/MW^2.h)	b ($/MWh)	c ($/h)	SC ($)	SD ($)
1	8	32	0.515	10.86	149.9	60	120
2	17	65	0.227	8.341	284.6	240	480
3	35	150	0.082	9.9441	495.8	550	1100
4	30	150	0.074	12.44	388.9	550	1100

As mentioned, the production cost (PRC) is considered as the output variable while the load capacity of a generator (LCG), incremental fuel cost (IC) and start-up cost (SUC) are taken as input variables. It is important to note that the ranges of each subset are selected after some experiments in a subjective manner. For example, if the load range that can be served by the largest generator is between 0 to 150 MW, Then low LCG could be chosen within a range of 0–35 MW. This allows a relative and virtual evaluation of the linguistic definitions with the numerical values. Similarly, the subsets for other variables can be linguistically defined and it is clear that the range of LCG and PRC is wider than IC and SUC. Therefore, five zones are made for both LCG and PRC fuzzy variables and three zones for the narrow variables (IC and SUC).

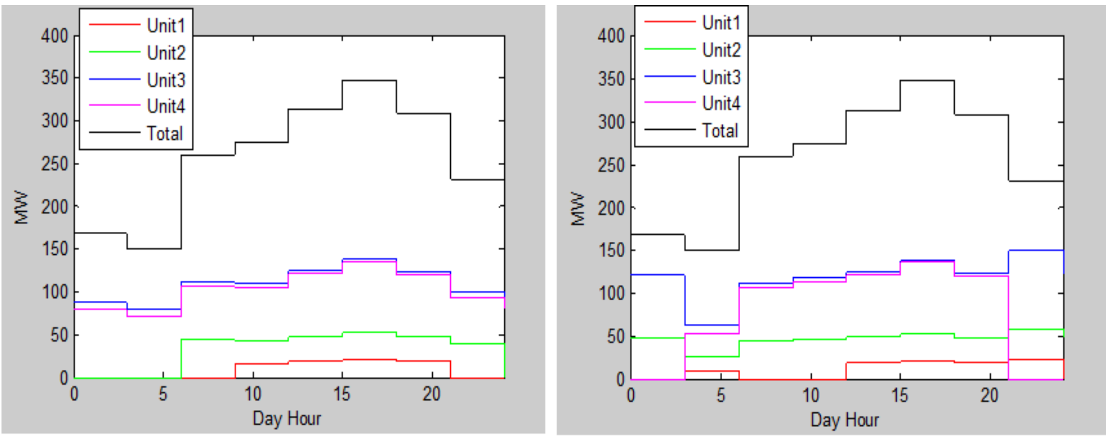
5.6.1 Four-Generating-Units Simulation Result

The algorithm for the unit commitment problem of the four-generating units at the Tuncbilek thermal power plant in Turkey is formulated applying the fuzzy logic. A MATLAB computer program to solve the problem was developed. The results obtained by the fuzzy logic approach provide crisp values of the production cost in each period for every given fuzzy input variables. The complete set of results, for the given load demand are summarized in Table 5-4.

Table 5-4: Generation schedule of the four units plant and production costs.

Period	Demand (MW)	FLA Commitment		DP – FDP Commitment		
		Combinations	Cost ($)	Combinations	FDP ($)	DP ($)
1	168	0 1 1 0	3977.29	0 0 1 1	4449.65	4343.57
2	150	1 1 1 1	3740.68	0 0 1 1	4148.06	3438.31
3	260	0 1 1 1	6104.21	0 1 1 1	6510.51	6736.43
4	275	0 1 1 1	5984.21	1 1 1 1	6493.76	6848.95
5	313	1 1 1 1	6954.98	1 1 1 1	7230.98	7747.68
6	347	1 1 1 1	7780.28	1 1 1 1	7298.00	8815.98
7	308	1 1 1 1	6141.76	1 1 1 1	6493.76	7596.66
8	231	1 1 1 0	5133.15	0 1 1 1	6409.98	5544.93
		Sum	45816.6	Sum	49034.7	51072.5

Note that the above tables show unit combinations and power allocation for each unit and in the next figure how much each unit generates and its corresponding operation schedule over a day.

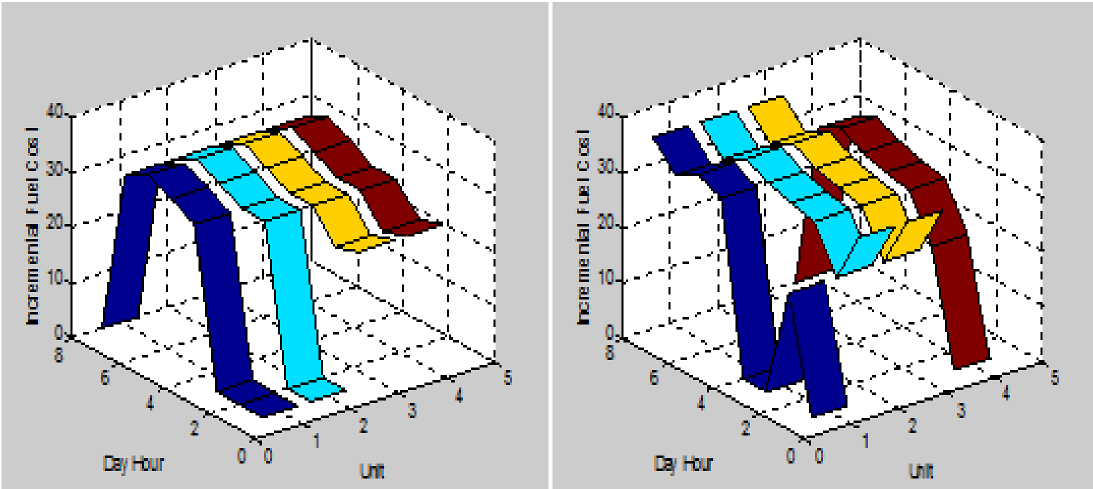


a) **b)**

Figure 5-6: Unit Commitment for 4-Units Model

a) Dynamic and Fuzzy Dynamic programming, b) Fuzzy logic Based approach

Other description of operation is fuel consumption or in other meaning incremental fuel cost curves corresponding to operation condition at each stage which was shown in Figure 5-7

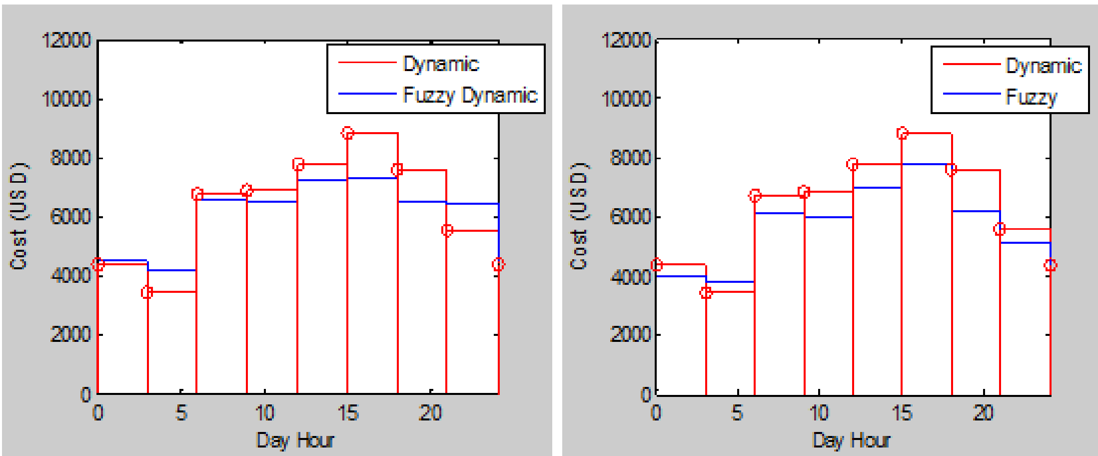


a) b)

Figure 5-7: Incremental Fuel Cost for 4-Units Model

a) Dynamic and Fuzzy Dynamic programming, b) Fuzzy logic approach

Next figure shows a cost comparison between dynamic programming and Fuzzy dynamic programming that obtained by first implemented algorithm, and also between dynamic programming versus fuzzy logic approach that obtained by next algorithm.



a) b)

Figure 5-8: Cost comparison for 4-Units Model

a) Dynamic and fuzzy dynamic programming, b) Dynamic and fuzzy logic approach

5.7 Ten-Generating-Units Model

The Tuncbilek thermal power plant in Turkey contains ten generating units which have been considered as case study with a reasonable number of units and daily load demand which divided into twenty four hours. Table 5-5 contains this load demand [29] while Figure (5-10) graphs this demand. As mentioned before, the problem will be solved applying the dynamic programming and fuzzy logic approaches and so the results will be documented and compared.

Table (5-5): Load data for Ten-unit Tuncbilek thermal plant (MW)

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

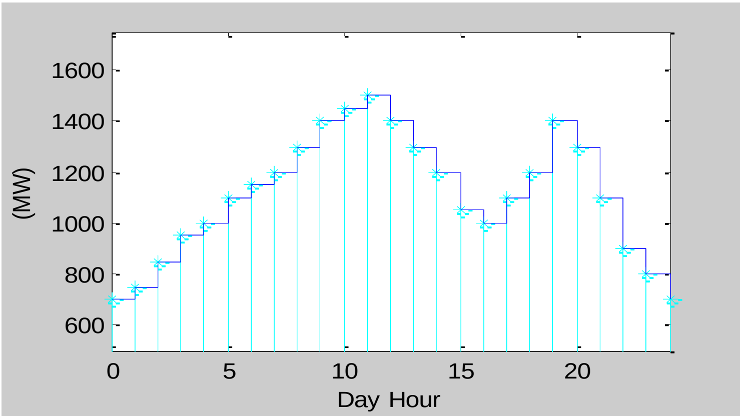


Figure 5-9: Daily load demand over 24 hours for the ten-units model

The characteristics of these ten generating units including cost coefficients, maximum and minimum real power generation, start-up cost, and ramp rates of each unit of the Tuncbilek power plant are given in Table 5-6.

Table 5-6: Unit characteristics for Ten-unit Tuncbilek thermal plant

Unit #	**Generation Limits**		**Running Cost**			**Start-up Cost**	
	Pmin (MW)	**Pmax (MW)**	**a ($/MW^2.h)**	**b ($/MW.h)**	**c ($/h)**	**SC ($)**	**SD ($)**
1	**150**	**455**	**0.00048**	**16.19**	**1000**	**4500**	**9000**
2	**150**	**455**	**0.00031**	**17.26**	**970**	**5000**	**10000**
3	**20**	**130**	**0.00200**	**16.60**	**700**	**550**	**1100**
4	**20**	**130**	**0.00211**	**16.50**	**680**	**560**	**1120**
5	**25**	**162**	**0.00398**	**19.70**	**450**	**900**	**1800**
6	**20**	**80**	**0.00712**	**22.26**	**370**	**170**	**340**
7	**25**	**85**	**0.00790**	**27.74**	**480**	**260**	**520**
8	**10**	**55**	**0.00413**	**25.92**	**660**	**30**	**60**
9	**10**	**55**	**0.00222**	**27.27**	**665**	**30**	**60**
10	**10**	**55**	**0.00173**	**27.79**	**670**	**30**	**60**

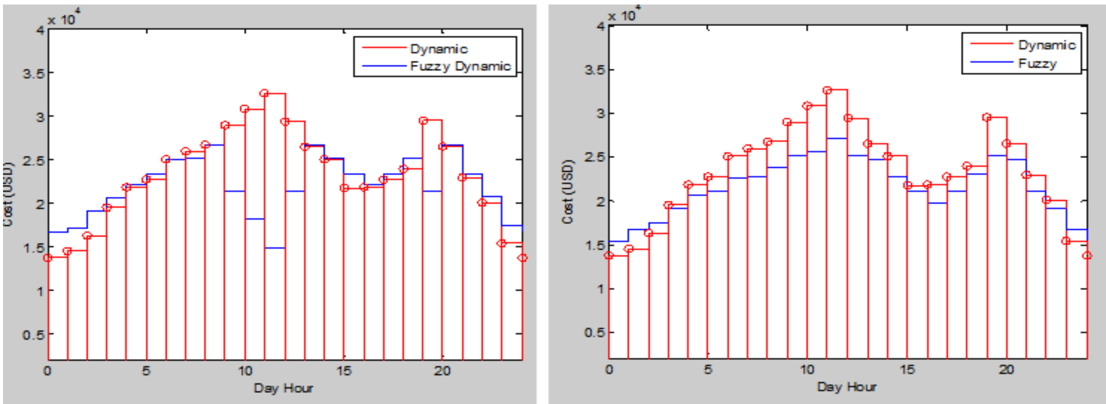
5.7.1 Ten-Generating-Units Simulation Results

Applying fuzzy logic approach to the taken Tuncbilek ten units thermal plant, the complete set of results, for the given load demand are summarized in Table 5-7.

Table 5-7: UC schedule for DP, FDP and FLA and corresponding production cost

Dynamic and Fuzzy Dynamic Programming Commitment				FLA Commitment	
Period	**Combination**	**DP cost($)**	**FDP cost($)**	**Combination**	**Cost ($)**
1	1100000000	**13683.13**	**16729.5**	1100000000	**15411**
2	1100000000	**14554.5**	**17040**	1100000000	**16691**
3	1100000000	**16301.89**	**19179**	1100100000	**17353**
4	1100100000	**19497.67**	**20628**	1100100000	**19017**
5	1101000000	**21872.77**	**22077**	1101100000	**20665**
6	1101100000	**22760.29**	**23388**	1111100000	**21013**
7	1111000000	**25105.04**	**25044**	1111100000	**22613**
8	1101100000	**25917.85**	**25216.5**	1111100000	**22677**
9	1111100000	**26734.02**	**26700**	1111111100	**23703**
10	1111110000	**28938.21**	**21387**	1111111100	**25175**
11	1111111000	**30853.51**	**18213**	1111111110	**25590**
12	1111111100	**32580.09**	**14832**	1111111111	**27024**
13	1111110000	**29348.21**	**21387**	1111111100	**25175**
14	1111100000	**26524.02**	**26700**	1111111000	**24755**
15	1101100000	**25017.85**	**25182**	1111100000	**22677**
16	1100100000	**21759.31**	**23353.5**	1111100000	**21013**
17	1101000000	**21872.77**	**22077**	1111100000	**19733**
18	1101100000	**22760.29**	**23388**	1111100000	**21013**
19	1101100000	**23917.85**	**25182**	1111110000	**23067**
20	1111110000	**29488.21**	**21387**	1111111100	**25175**
21	1111100000	**26524.02**	**26700**	1111111000	**24755**
22	1101100000	**22960.29**	**23353.5**	1100111000	**21095**
23	1100000000	**20097.91**	**20697**	1100100000	**19017**
24	1100000000	**15427.42**	**17419.5**	1100000000	**16691**
	Total Sum	**564497.12**	**527260.5**	**Total Sum**	**521098**

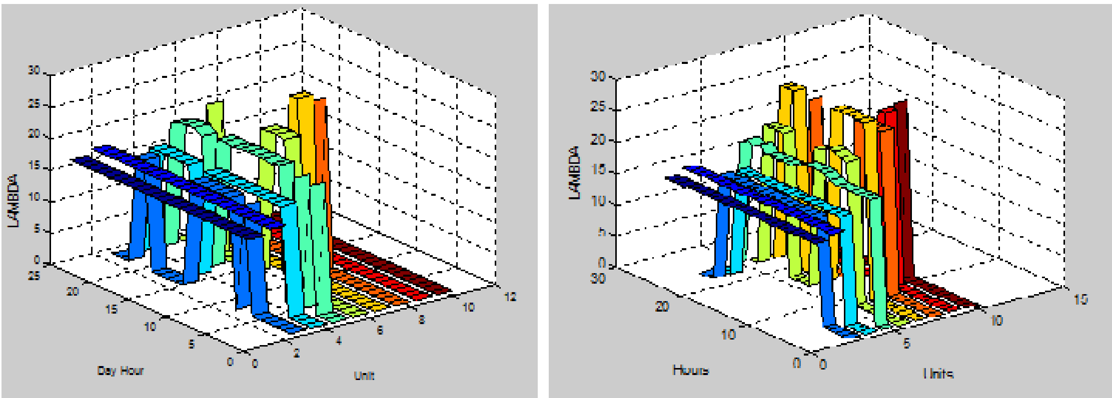
Figure (5-10) described the obtained cost by two presented algorithms compared with dynamic programming and this show the effectiveness of fuzzy approach over dynamic programming.



a) b)

Figure 5-10: Cost obtained by FLA, DP and FDP for the ten-unit model
a) Dynamic vs. Fuzzy Dynamic Programming, b) Dynamic vs. Fuzzy Logic Approach

Figure (5-11), described the status of each unit by showing the incremental fuel cost changing for each unit at day hour.



a) b)

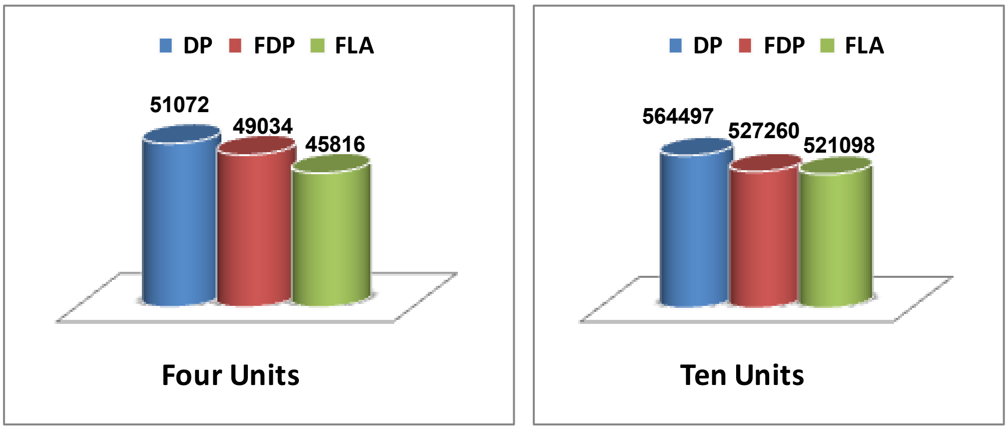
Figure 5-11: Incremental fuel cost for the ten unit thermal plant
a) Dynamic and Fuzzy Dynamic Programming, b) Fuzzy Logic Approach

5.8 Production Cost Comparison

The obtained results show that the proposed method gives better figures when compared to previous methods for both models. Table 5-8 contains the overall daily and annual savings accomplished.

Table 5-8: Production Cost Comparison

Plant	Daily Cost ($)			Yearly Savings (S)	
	DP	FDP	FLA	FDP	FLA
Four Units	51072.5	49034.7	45816.56	7.25456×10^{5}	18.71114×10^{5}
Ten Units	564497.12	527260.5	521098	1.3256×10^{7}	1.5450×10^{7}



a) **b)**

Figure 5-12: Cost comparison for each model
a) Four generating-units model, b) Ten generating-units model

Figure 5-12 displays graphically the cost comparison for the four- and ten-units models for the dynamic programming and the proposed method. It is obvious that the production cost obtained by the proposed technique is lower than the dynamic programming.

CHAPTER 6
CONCLUSION

6.1 Conclusion

The purpose of this work was to develop and apply a new approach for handling the mathematical model of the unit commitment problem in power system planning and to compare the outcomes with the results achieved by the traditional dynamic programming method.

A different fuzzy linguistic description of the unit commitment is formulated successfully that supersedes previous descriptions by its wide and accurate rules which relate three fuzzy input variables with output fuzzy production cost variable and hence the developed algorithms based on fuzzy logic are effectively applied to solve unit commitment problem of two different size models of Tuncbilek power plant in Turkey. The first plant contains four generating units with eight periods of demand and the second plant contains ten units with more realistic demand distributed over the 24 hours of the day. A MATLAB program is developed that gather plant information such as cost coefficient and load demand and other system constraints in order to get an effective results on both two models that have lower production cost than dynamic programming either by fuzzy dynamic programming or by fuzzy logic approach.

Here, it is important to note that we have a significant saving in production cost which is about 4% when fuzzy dynamic programming applied on four generating units and compared with conventional dynamic programming and about 10% when fuzzy logic approach applied on same system and compared with dynamic programming. But when ten generating units model used, savings was about 7% in cost at fuzzy dynamic programming case compared with dynamic programming and about 8% by comparing fuzzy logic approach with conventional dynamic programming. This means that increasing system units results in higher saving in the production cost.

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APPENDIX A

PLANTS CHARACTERISTICS AND COMMITMENT

Table A-1: Unit characteristics for Four-unit Tuncbilek thermal plant

Unit No.	Generation Limits		Running Cost			Start-up Cost		Ramp Rates	
	Pmin (MW)	Pmax (MW)	A ($/MW^2.h)	B ($/MWh)	C ($/h)	SC ($)	SD ($)	RU (MW/h)	RD (MW/h)
1	8	32	0.515	10.86	149.9	60	120	6	6
2	17	65	0.227	8.341	284.6	240	480	14	14
3	35	150	0.082	9.9441	495.8	550	1100	30	30
4	30	150	0.074	12.44	388.9	550	1100	30	30

Table A-2: Unit characteristics for Ten-unit Tuncbilek thermal plant

Unit #	Generation Limits		Running Cost			Start-up Cost		Ramp Rates	
	Pmin (MW)	Pmax (MW)	A ($/MW^2.h)	B ($/MW.h)	C ($/h)	SC ($)	SD ($)	RU (MW/h)	RD (MW/h)
1	150	455	0.00048	16.19	1000	4500	9000	130	130
2	150	455	0.00031	17.26	970	5000	10000	130	130
3	20	130	0.00200	16.60	700	550	1100	60	60
4	20	130	0.00211	16.50	680	560	1120	60	60
5	25	162	0.00398	19.70	450	900	1800	90	90
6	20	80	0.00712	22.26	370	170	340	40	40
7	25	85	0.00790	27.74	480	260	520	40	40
8	10	55	0.00413	25.92	660	30	60	40	40
9	10	55	0.00222	27.27	665	30	60	40	40
10	10	55	0.00173	27.79	670	30	60	40	40

APPENDIX B
UNIT COMMITMENT

Table B-1: Power allocation for each of four-unit's plant in case of FLA, DP and FDP

Period	Demand (MW)	FLA				DP – FDP			
		U1	U2	U3	U4	U1	U2	U3	U4
1	168	0	47.18	120.8	0	0	0	87.69	80.30
2	150	9.06	26.10	62.48	52.37	0	0	79.15	70.84
3	260	0	43.52	110.7	105.8	0	43.51	110.6	105.7
4	275	0	45.71	116.7	112.5	16.63	43.27	110.0	105.0
5	313	18.93	48.50	124.5	121.1	18.93	48.49	124.4	121.0
6	347	20.99	53.17	137.4	135.4	20.99	53.17	137.4	135.4
7	308	18.63	47.81	122.6	118.9	18.62	47.81	122.5	118.9
8	231	23.08	57.92	150.0	0	0	39.27	98.94	92.77

Table B-2: Power allocation for each of ten-unit's plant in case of FLA, DP and FDP

Time	MW	Fuzzy Logic Approach										Dynamic and Fuzzy Dynamic Programming									
		U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	700	455	245	0	0	0	0	0	0	0	0	455	245	0	0	0	0	0	0	0	0
2	750	455	295	0	0	0	0	0	0	0	0	455	295	0	0	0	0	0	0	0	0
3	850	455	370	0	0	25	0	0	0	0	0	455	395	0	0	0	0	0	0	0	0
4	950	455	455	0	130	40	0	0	0	0	0	455	455	0	0	40	0	0	0	0	0
5	1000	455	390	0	130	25	0	0	0	0	0	455	415	0	130	0	0	0	0	0	0
6	1100	455	360	130	130	25	0	0	0	0	0	455	455	0	130	60	0	0	0	0	0
7	1150	455	410	130	130	25	0	0	0	0	0	455	435	130	130	0	0	0	0	0	0
8	1200	455	455	130	130	30	0	0	0	0	0	455	455	0	130	160	0	0	0	0	0
9	1300	455	455	130	130	75	20	25	10	0	0	455	455	130	130	130	0	0	0	0	0
10	1400	455	455	130	130	162	33	25	10	0	0	455	455	130	130	162	68	0	0	0	0
11	1450	455	455	130	130	162	73	25	10	10	0	455	455	130	130	162	80	38	0	0	0
12	1500	455	455	130	130	162	80	25	43	10	10	455	455	130	130	162	80	33	55	0	0
13	1400	455	455	130	130	162	33	25	10	0	0	455	455	130	130	162	68	0	0	0	0
14	1300	455	455	130	130	85	20	25	0	0	0	455	455	130	130	130	0	0	0	0	0
15	1200	455	455	130	130	30	0	0	0	0	0	455	455	0	130	160	0	0	0	0	0
16	1050	455	310	130	130	25	0	0	0	0	0	455	455	0	0	140	0	0	0	0	0
17	1000	455	260	130	130	25	0	0	0	0	0	455	415	0	130	0	0	0	0	0	0
18	1100	455	360	130	130	25	0	0	0	0	0	455	455	0	130	60	0	0	0	0	0
19	1200	455	440	130	130	25	20	0	0	0	0	455	455	0	130	160	0	0	0	0	0
20	1400	455	455	130	130	162	33	25	10	0	0	455	455	130	130	162	68	0	0	0	0
21	1300	455	455	130	130	85	20	25	0	0	0	455	455	130	130	130	0	0	0	0	0
22	1100	455	455	0	0	20	25	0	0	0	0	455	455	0	130	60	0	0	0	0	0
23	900	455	420	0	0	0	0	0	0	0	0	455	445	0	0	0	0	0	0	0	0
24	800	455	345	0	0	0	0	0	0	0	0	455	345	0	0	0	0	0	0	0	0