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Implementing Fuzzy-Logic to Solve the Unit-Commitment Problem of a Ten-Unit Thermal Generation Plant

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ABSTRACT

This paper presents an implementation of fuzzy-logic to solve the unit-commitment problem of thermal generation plant with the main objective of obtaining a feasible unit combination for each loading condition while subjected to a variety of constraints. The model in this study contains ten-generation units and the daily load demand is subdivided into 24 intervals. The unit combinations and the corresponding generation scheduling intend to minimize the operating cost. The implementation of fuzzy-logic allows a qualitative description of the behavior of the system: the system's characteristics and the response without the need for exact mathematical formulations. The numerical values obtained by the fuzzy-logic approach are compared with those obtained by the dynamic programming. The results have shown that the proposed fuzzy-based approach provides feasible combinations of the generation units and economical cost of operation of these units and have also shown the superiority of the proposed fuzzy-logic approach over the dynamic programming.

Keywords: *Fuzzy-logic, unit-commitment, load curve, and dynamic programming*

1. INTRODUCTION

Investments in power systems are quite expensive and the resources needed to operate them are rapidly becoming sparser. Therefore, the focus today is on optimizing the operating cost of power stations. In present world, meeting the power demand as well as optimizing generation has become necessities. Unit-commitment (UC) in power system refers to the optimization problem for determining the turning on/ turning off states of thermal power generating units that minimize the operating cost subject to variety of constraints for a given time periods [1]. The solution of the unit-commitment problem (UCP) is a complex optimization problem. The exact solution of the UCP can be obtained by complete enumeration of all feasible combinations of generating units, which could be a huge number. The unit-commitment is commonly formulated as a non–linear, large scale, mixed integer combinational optimization problem. One important aspect to realize the problem is load curves or especially the daily load curve which is a graph shows the variation in demand along 24 hour time horizon, that is describe many characteristics of the system as maximum demand or peak, base load and the average load needed to supply by the generation plant [1].

Summary of the different methods used in the solution of the UC problem may be found in Fahd [2]. The DP method as in Hobbs and Huang [3, 4] based on priority list is flexible, but the computational time suffers from dimensionality. As Zhuang and Redondo, Lagrangian relaxation (LR) for UCP [5, 6] was superior to DP due to its higher solution quality and faster computational time. However, Dekranjanpetch said that numerical convergence and solution quality of LR are not satisfactory when identical units exist [7]. With the advent of heuristic approaches, genetic algorithm (GA) as Kazarlis [8], evolutionary programming (EP) as Juste [9], simulated annealing (SA) as Mantawy [10], tabu search (TS) as Selim Shokri [11], hybrid dynamic programming as Kumar [12], and also modified sub-gradient method (MSG) as Kurban in [13] have been proposed and implemented to solve the UC problems. The results obtained by GA, EP, TS, SA or MSG required a considerable amount of computational time especially for large system size.

The use of fuzzy-logic has received increased attention in recent years because of its worth in dropping the requirement for difficult mathematical models in problem solving. Relatively, fuzzy-logic employs linguistic terms, which deal with the causal 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 hard to solve. Moreover, fuzzy-logic as a new technique, which approximates reasoning, while allowing decisions to be made efficiently. To accomplish a good unit-commitment planning with the use of fuzz-logic, the generation cost and the load demand are specified as fuzzy-set notation. The outcome of the fuzzy-logic implementation is the desired commitment schedule.

In a previous study, a four-thermal-generation-units model with a load demand subdivided into eight time periods has been employed [14, 15]. The findings were encouraging and the fuzzy-logic approach has provided a logical, a feasible, and an economical unit combination for each time period. In this paper, a thermal power generation plant that contains ten units is used as a test model which is more realistic than the four-units-model in three aspects according to [14]. First, the exact solution would take longer time and would be harder to choose among the terrific number of combinations, the second is the number of generation units is more than doubled and third the daily load demand is subdivided into 24 time periods which is more accurate than the eight time periods of the four-units-model. This study is curried out using the ten-

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generation-units thermal power plant of Tuncbilek in Turkey is chosen as test model.

2. THE UNIT-COMMITMENT PROBLEM

The unit-commitment problem can mathematically be described as given below in Equation (1).

$$Min\ F_i(P_i^t, U_i^t) = \sum_t \sum_i [(a_i P^2 + b_i P + c_i) + SUC_i^t (1 - U_i^{t-1})] U_i^t \quad (1)$$

Where: $F_i(P_i^t)$ is generator fuel cost function in quadratic form, a_i , b_i and c_i are coefficients of unit i, and P_i^t is the power generation of unit i at time t and U_i^t is the unit status at the specified time period.

2.1 Problem Constraints

The minimization of the objective function must satisfy two kinds of constraints and these are the system constraints and the units' constraints and these constraints are described in the following two subsections.

2.1.1 System Constraints

a. Power balance constraint: during each time period, the power generated by the corresponding feasible unit combination must meet exactly the forecasted load demand. This power balance is given in Equation (2) where the total power demand at a certain period is P_D^t .

$$\sum_{i=1}^{N} P_i^t U_i^t - (P_D^t) = 0 \quad (2)$$

b. Hourly spinning reserve: there must be some units that are not turned on but ready for commitment at each time period during the course of the day and this spinning reserve R is given below in Equation (3).

$$\sum_{i=1}^{N} P_i^{max} U_i - (P_D) = R \quad t = 1, 2, 3 \ldots T \quad (3)$$

Where t is the time period (varies from 1 to 24 during the course of the day) and T is the number of the selected time periods.

2.1.2 Unit Constraints

a. Generation limits: each of the generation units has a certain generation capacity and this capacity must be satisfied and must not be violated during any time period when the unit is turned on. This constraint is expressed mathematically in Equation (4).

$$P_i^{min} U_i^t \leq P_i \leq P_i^{max} U_i^t \quad i = 1, 2, 3 \ldots N \quad (4)$$

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

b. Ramp-up and ramp-down constraints: To avoid damaging the turbine, the electrical output of a unit cannot change by more than a certain amount over a period of time. Here for each unit, output is limited by ramp up/down rate at each hour as follows in Equation (5) and Equation (6):

$$P_i^{t-1} - P_i^t \leq RD_i \quad if \quad (U_i^t = 1) \,\&\, (U_i^{t-1} = 1) \quad (5)$$
$$P_i^t - P_i^{t-1} \leq RU_i \quad if \quad (U_i^t = 1) \,\&\, (U_i^{t-1} = 1) \quad (6)$$

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

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 normal 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.

3.1 Fuzzy-Logic and the UCP

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. In the following, a brief description and explanation of mentioned fuzzy variables are presented:

- 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 offline. It is important to mention that we include the start, shut down, maintenance costs and crew expenses of each unit as a fixed value that is start-up cost. So, the start-up cost of a unit is independent of time even when 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

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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 describing the physical process variables.

3.2 Fuzzy Set Associated with the Unit-Commitment

After identifying the fuzzy variables associated with the 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 as follows:

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

The incremental fuel cost is stated by the following set:

IC = {Zero, Small, Large}

The sets representing the start–up cost are shown below:

SUC = {Low, Medium, High}

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 (1). 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.

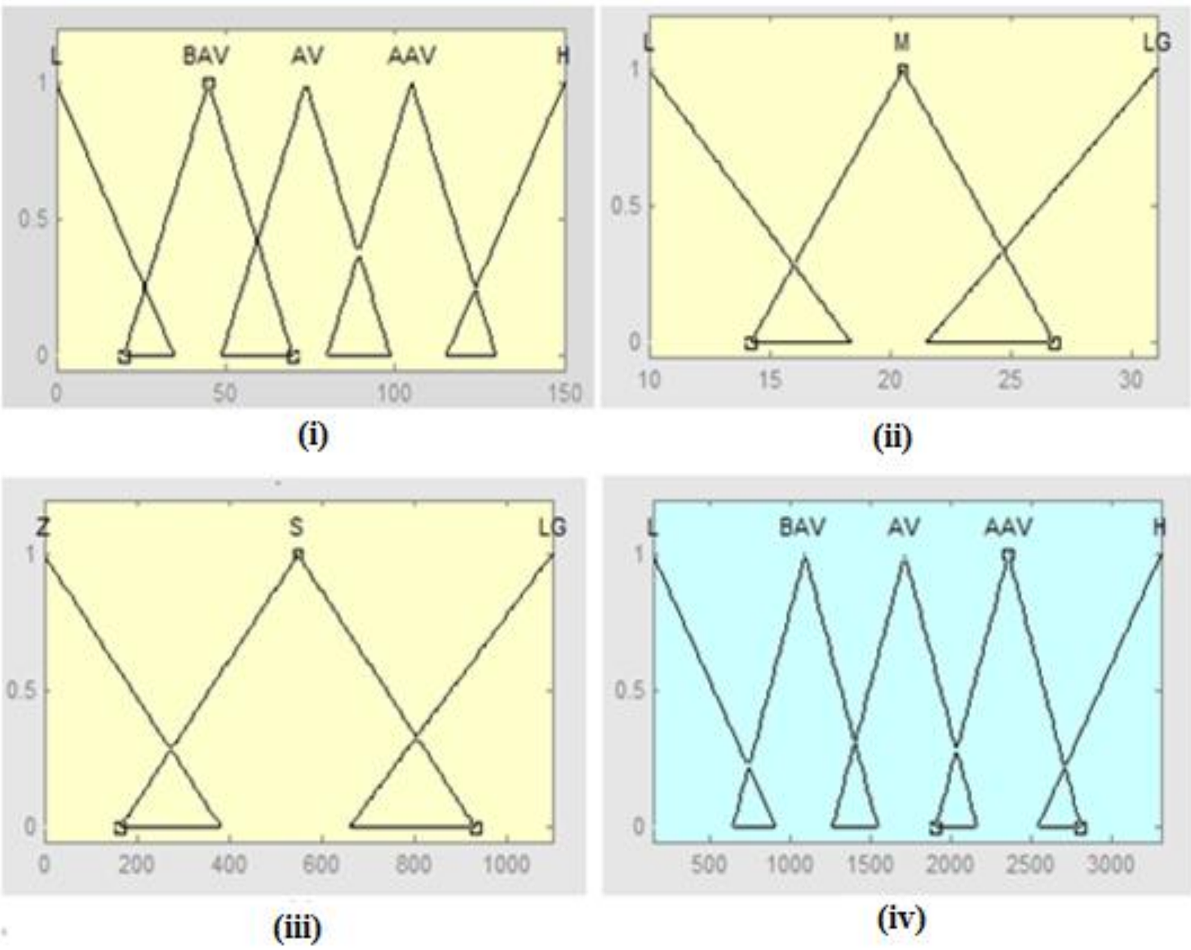

Fig 1: Membership Functions of Input / Output Variables
(i) LCG Membership (ii) IC Membership (iii) SUC Membership (iv) PRC Membership

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3.2.1 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. The If (condition) is an antecedent to the Then (consequence) of each rule. 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,

$$PRC = LCG \cap IFC \cap SUC$$

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

$$\mu\, PRC = \mu\, LCG \cap \mu\, IFC \cap \mu\, SUC \quad \text{Or}$$
$$\mu\, PRC = \min\{\mu\, LCG, \mu\, IFC, \mu\, SUC\}$$

Where μ LCG, μ IC and μ SUC are memberships of load capacity of the generator, incremental fuel cost and start–up cost, respectively.

Using the above notation, fuzzy rules that associate fuzzy input variables with the fuzzy output variable are written. Based upon these relationships and with reference to Figure (1), the total sum of rules are 45 that could be composed because there are five subsets for load capacity of the generator, three subsets for incremental fuel cost and three subsets for start–up cost (5 × 3 × 3 = 45):

Table 1: Fuzzy Rules of Input / Output Fuzzy Variables

Rule No.	LCG	IC	SUC	PRC	Rule No.	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					

Rule 17 as an example could be written as follows: If (load capacity of the generator is below average, and incremental fuel cost is large and start–up cost is small), then production cost is below average. So, the fuzzy results must be defuzzified by a certain defuzzification method after relating the input variables to the output variable as in Table (1). That is called a defuzzification process to achieve crisp numerical values.

3.2.2 Defuzzification Process

There are several used, logically meaningful, and practically effective defuzzification formulas available, which are by nature weighted average formulas in various forms [12]. One of the most commonly used methods of defuzzification is the centroid or center of gravity method, which returns the center of area under the curve and it is very accurate method [13]. So, centroid is preferred according accuracy and satisfying inference membership hypotheses in a good manner. Accordingly the production cost will be as in Equation (7) below:

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

(7)

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

4. FUZZY-LOGIC BASED-APPROACH ALGORITHM

In solving the UCP, two types of variables must be treated: the first type is the units' states at each period U_i^t which are integer or binary (0 – 1), 0 for off sate and 1 for on state) and the second type is the units' output powers P_i^t which are continuous variables need to be determined. This problem can be handled and subdivided into two problems: the first is combinatorial optimization problem in U and the other is a non-linear one in P.

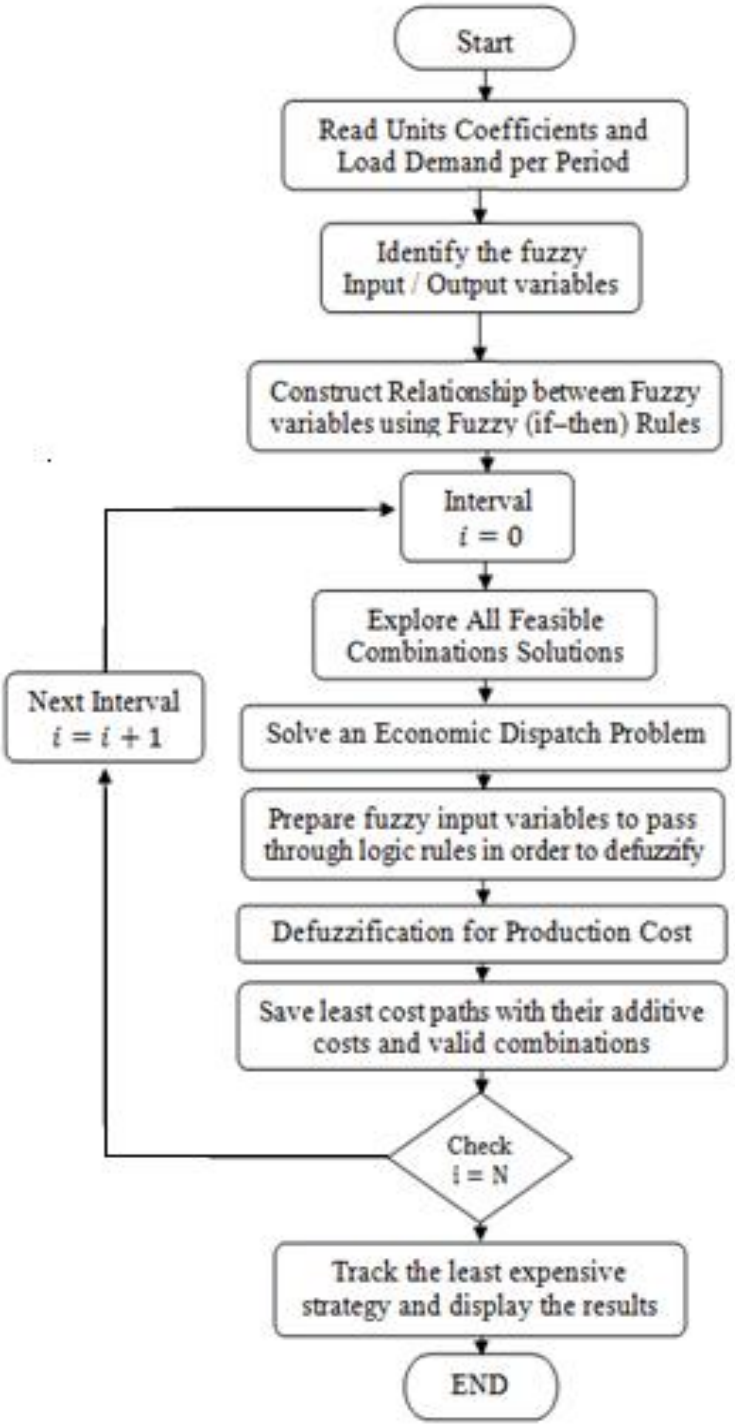

Fig 2: Flow Chart of the Fuzzy-Logic-Based Approach

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A Fuzzy Based Approach is proposed and implemented to solve this complicated optimization problem. The economic dispatch is simultaneously solved via a quadratic programming routine. Figure (2) shows the flowchart of the proposed algorithm. From the flowchart, it can be seen that the proposed technique is not much different from the hybrid fuzzy dynamic programming [14]. This is true unless it gives an alternative unit combinations and so different total production cost. This is due to bringing the defuzzification process forward inside the check loop. So, the results obtained provide different unit combinations based on both the fuzzy-logic approach and the dynamic programming method.

5. TEN-THERMAL-GENERATION-UNITS MODEL (CASE STUDY)

The values of the daily load demand of the ten-generation-units plant of Tuncbilek, Turkey thermal power plant are shown in Table (2) and graphically depicted in Figure (3). These values are subdivided into 24 time periods [14] and for each time period the load demand is assumed to be constant and this assumption is more realistic than that of the four-unit model presented in a previous study [18].

Table 2: Load Demand for the Ten-Units-Plant (MW)

Hour	0	1	2	3	4	5	6	7	8	9	10	11
Demand	700	750	850	950	1000	1100	1150	1200	1300	1400	1450	1500
Hour	12	13	14	15	16	17	18	19	20	21	22	23
Demand	1400	1300	1200	1050	1000	1100	1200	1400	1300	1100	900	800

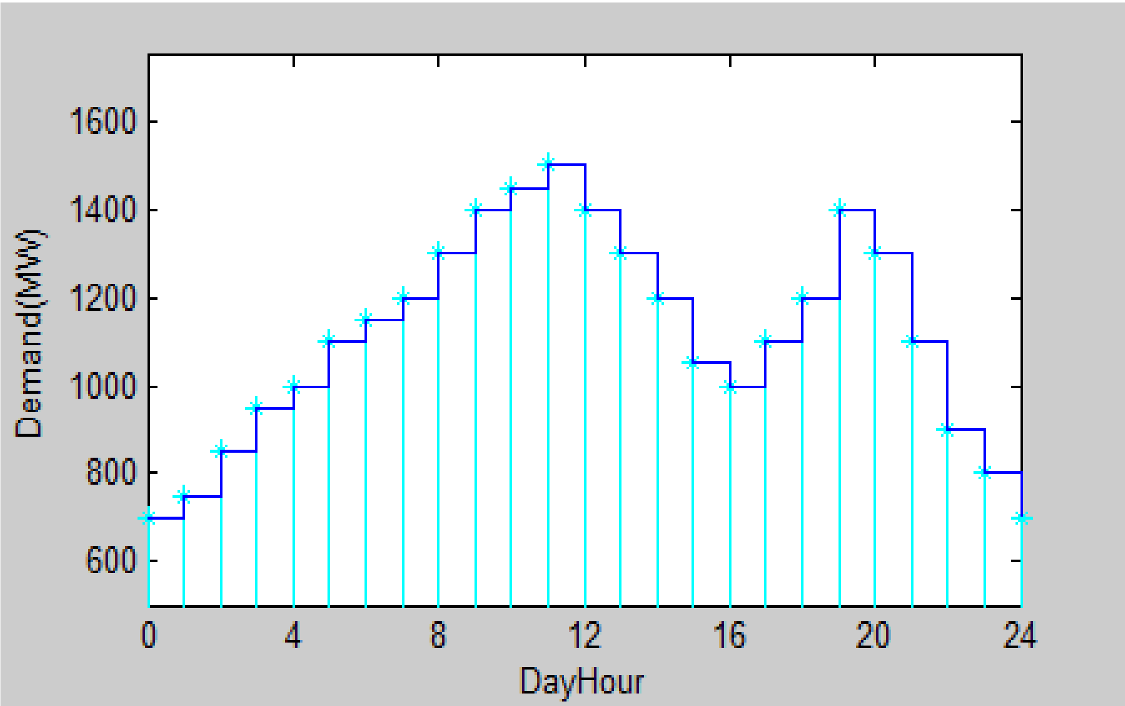

Fig 3: Load Demand for the Ten-Units-Plant

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The characteristics of these ten generating units including minimum and maximum real power generation, cost coefficients, start-up cost (SU+SD), and ramp rates of each unit are given in Table (3).

Table 3: Characteristics of the Ten Generation Units

Unit #	Generation Limits		Running Cost			Start-up Cost		Ramp rates	
	Pmin (MW)	Pmax (MW)	A ($/MW^{2}h)	B ($/MWh)	C ($/h)	SU ($)	SD ($)	RD (MW/h)	RU (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

The fuzzy-logic is implemented using the production cost as the output variable, and the load capacity of generator, incremental fuel cost and start–up cost as input variables. The fuzzy sets describing these variables are shown in Figure (1). At this instant, it is important to note that we choose the ranges of each subset 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 300 MW, Then low LCG could be chosen within a range of 0 MW – 60 MW and 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 are wider than IC and SUC. Therefore, five zones for each wide fuzzy variable and three zones only for other narrower ones are made [16].

6. SIMULATION RESULTS

The algorithm for the unit-commitment problem of the ten-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 unit combinations and crisp values for the production cost in each time interval for every given fuzzy input variables. The complete set of results, for the given load demand are summarized in Table (4).

Table 4: Unit Combinations and Production Costs

	Dynamic Programming Method		FLA Method	
Period	Combination	DP cost ($)	Combination	Cost ($)
1	1100000000	13683.13	1100000000	15411
2	1100000000	14554.5	1100000000	16691
3	1100000000	16301.89	1100100000	17353
4	1100100000	19497.67	1100100000	19017
5	1101000000	21872.77	1101100000	20665
6	1101100000	22760.29	1111100000	21013
7	1111000000	25105.04	1111100000	22613
8	1101100000	25917.85	1111100000	22677
9	1111100000	26734.02	1111111100	23703
10	1111110000	28938.21	1111111100	25175
11	1111111000	30853.51	1111111110	25590
12	1111111100	32580.09	1111111111	27024
13	1111110000	29348.21	1111111100	25175

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14	1111100000	26524.02	1111111000	24755
15	1101100000	25017.85	1111100000	22677
16	1100100000	21759.31	1111100000	21013
17	1101000000	21872.77	1111100000	19733
18	1101100000	22760.29	1111100000	21013
19	1101100000	23917.85	1111110000	23067
20	1111110000	29488.21	1111111100	25175
21	1111100000	26524.02	1111111000	24755
22	1101100000	22960.29	1100111000	21095
23	1100000000	20097.91	1100100000	19017
24	1100000000	15427.42	1100000000	16691
	Total Sum	564497.12	Total Sum	521098

For the purpose of comparison, the results obtained by the dynamic programming are also shown in the same table. The fuzzy-logic has provided different unit combinations in most time periods and consequently different production costs. The overall results of the fuzzy-logic approach are comparable and better than to those of dynamic programming. By observation, as the number of the needed generating units to meet the specific demand increases, the number of possible combination goes up significantly. So, the role of the fuzzy-logic appears in such cases, and therefore the fuzzy-logic performs better during the existence of more number of units in operation. Figure (4) shows graphically the production cost obtained by the dynamic programming and the fuzzy-logic approach.

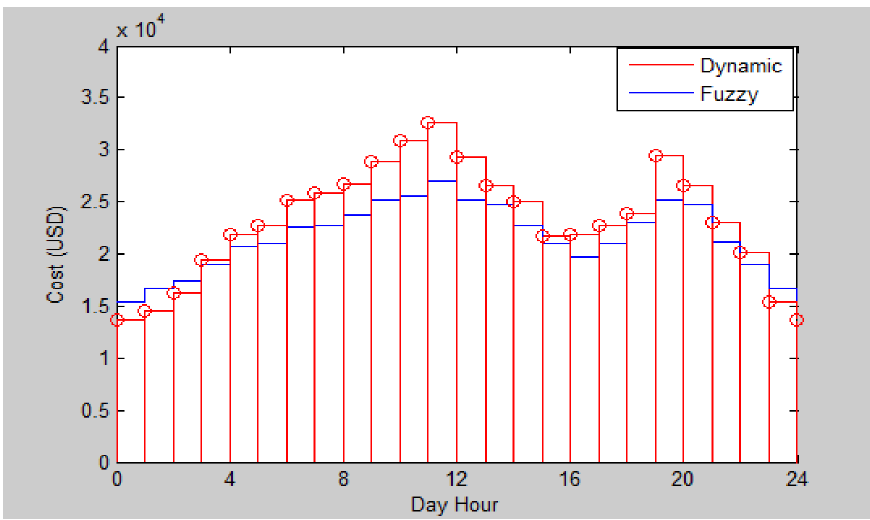

Fig 4: Production Cost

Another description of the mentioned operation is the fuel consumption or the incremental fuel cost curves corresponding to the operation condition at each time interval and these are depicted in Figure (5).

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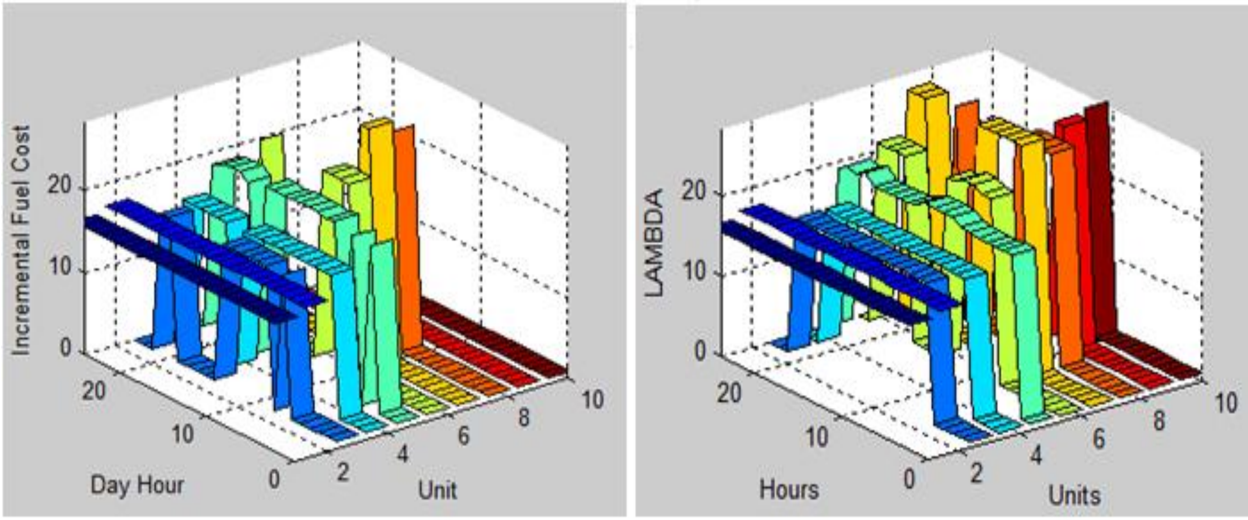

(i) (ii)

Fig 5: Incremental Fuel Cost
(i) Dynamic Programming (ii) Fuzzy-Logic

It is clear to see that the fuzzy-logic and the dynamic programming approaches have provided similar incremental fuel cost when they have the same unit combinations and different incremental fuel cost for different unit combinations which is the case for most time periods.

7. CONCLUSION

A fuzzy-logic-based approach has been developed for solving the unit-commitment of a ten-thermal-units power plant. The approach has been successfully implemented to the model with a daily load curve subdivided into 24 time periods. With reference to the previous study handling a four-units model with load demand subdivided into eight time periods, one can confidently state that the fuzzy-logic-based approach is applicable to power plants with larger number of generation units and even with more systems and units constraints. For the purpose of comparison, the results obtained by the fuzzy-logic approach are compared with those obtained by the dynamic programming method for the same model.

For each time interval, the fuzzy-logic approach provided a logical and feasible units combination and corresponding incremental fuel cost and production cost. The unit combinations are different than those provided by the dynamic programming in the majority of time periods and so the incremental fuel costs and the production costs. During a few number of time periods, the production costs provided by the fuzzy-logic approach are higher than those provided by the dynamic programming. However, the overall production cost obtained by the fuzzy-logic during the twenty-four time periods is lower than that of the dynamic programming. A daily saving in the production cost of $43399.12 is accomplished and this implies that a production cost reduction of 7.69% is achieved due to the application of the fuzzy-logic and when compared with the dynamic programming.

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