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Development of Fuzzy Logic Based Approach for Consumer Side Management in Smart Home

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Abstract: **Smart Grid environment requires the active participation of the consumer in terms of energy saving and shift the loads to off-peak period balance the power between source and load. In this situation, consumers' preferences, self-adjusting, and self-scheduling of the operation of home appliances drawing more attention because of difficulties in their manual adjustment. An autonomous scheduler is needed for the home appliances to function automatically to save cost and energy but without compromising the comfort level of the consumer. This work proposes a fuzzy logic based intelligent approach for providing suggestions to the consumer through shifting their electricity demands to off-peak hours. The proposed fuzzy logic-rule-based approach consists of time slices, bidding cost, power rating, duration of total operating hours of the individual loads per day, preferable and non-preferable time slots of loads as inputs, and ON/OFF of the loads as the output. Here, household appliances are categorized as base loads and schedulable loads. Consumer comfortability, cost, and demand responses are the three-optimization variables taken into account for the design of a fuzzy-based load management scheduler. The simulation result shows that the proposed system provides support to the consumer's decisions on controllable load management, considering the consumer's comfortability and rescheduling to achieve possible economic benefits.**

Keywords: Demand Response, Fuzzy logic, Smart Grid

I. INTRODUCTION

One of the applications of Smart Grid technology is Smart Home, which can provide various ways to save energy. It helps to reduce greenhouse gas emissions and energy usage at the same time. Smart homes are not only for savings in electrical energy, but also result in many benefits such as stability, increased level of comfort, improved home automation, and control of electricity.[1]

Figure 1 explains the architecture of a smart home with Demand Response (DR) signals. Intelligent controllers receive/send signals to home appliances and renewable energy sources. Weather conditions are also connected with intelligent controllers for maintaining the comfort level of the consumer. DR signal is received through Advanced Metering Infrastructure (AMI) from Utility.

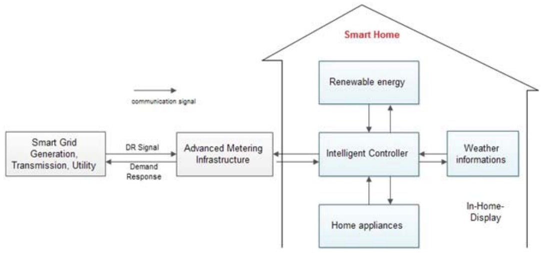

Fig.1-Schematic of Smart Home with DR signal

Demand Response (DR) is one of the consumer side management mechanism in which the end-users of electricity are encouraged to participate in reducing the peak load on the system by altering their normal energy consumption pattern. In return, end-users are given price or service incentives. Eventually, this process is expected to reduce the overall system peak load as end-users shift some of their loads from peak hours or high market price hours to off-peak hours or low market price hours. [2]

Participating in demand response has major benefits for both consumers and energy producers, i.e. saving the consumer from high power costs, and allowing utilities to reduce peak loads. Demand Response strategy aims to reduce the pressure kept on energy providers and to reduce the energy cost of the consumer. To maintain a balanced condition, it is necessary to adopt a demand-side load management system based on intelligent or optimization techniques. By adjusting the residential loads, Demand Side Management reacts quickly to the mismatches of supply and demand. Once the information and infrastructure for DR are made available, the consumer can apply the demand side load management algorithm to implement DSM strategy.

Many intelligent breakthroughs lead to the integration of smart HEMS with various functions inside the housing, such as automatic monitoring, smart meters, and lower energy consumption. Smart Home captures its importance due to concerns about global warming and energy shortages. In reality, it helps to reduce the demand for electricity during peak load hours [3]. The various components associated with Smart Home are smart meter, energy management system, energy storage, smart appliances, and distributed generation. A thorough study of the advantages and disadvantages of the implemented smart grid pilot projects in Brazil was done in [4]. The Active Demand Side Management (ADSM), smart transmission, distribution, and generations are also discussed. The consumer can control the home appliances based on the DR signal received from the energy provider [5]. The authors suggested only an idea and no real-time implementation was adopted.

A rule-based Home Energy management algorithm was developed and integrated with a load controller in the laboratory [6]. It speaks about how much power could be reduced by setting the consumer preferences. The loads will be activated based on the designed algorithm and not on the real-time price. A prototype of a hardware-based Home Energy Management System (HEMS) was developed with the help of a machine learning algorithm and sensing technology to minimize the energy cost and control the loads intelligently [7]. Hardware architecture to enable and disable the air-conditioning unit by varying thermostat set point through Wi-Fi, Real-time energy cost was not taken into account [8]. A laboratory hardware smart home simulator was developed using Raspberry Pi in the laboratory of the University "Politehnica" of Bucharest, which could able to respond to the supplier's signal [9]. The hardware realization of Home Energy Management for household appliances with preset priority is demonstrated in [10]. Priority is fixed based on the usage and not on the period and real-time prices.

To reduce the cost of energy consumption, a Home Energy Management scheduler was proposed that works under three different phases namely Real-time Monitoring, stochastic scheduling, and real-time control [11]. In the calculation of the overall energy consumption costs and to select a set of home control devices, stochastic dynamic programming is used. Finally, the controllable loads of the household are displayed in real-time using real-time monitoring. However, the intelligent algorithm implemented is complex, with a high computational load and low speed. Home Energy management using bespoke software was developed to turn on/off and monitor the home appliances [12]. The developed system aims to raise awareness about power usage. This software is compatible with Linux and is written in Java, Python, and HTML.

One of the major features of Smart Grid technology is the integration of renewable energy resources [13]. In [14] a Smart Home was developed with the integration of PV and storage energy resources. The energy requirement of Smart Home has been managed by installing Photovoltaic and Batteries. The power consumption management system is maintained by a self-learning feedback mechanism. PV systems will interact with the home appliances to maintain comfortability.

Several AI strategies have been adopted to develop a scheduler for home appliances. Artificial Intelligence (AI) uses computer programming that mimics and understands human intelligence [15-17]. Artificial Neural Network is a branch of AI, which is an information processing system that helps to stimulate the nonlinear system and stimulates the human brain [18]. The fuzzy logic controller is easy to execute, can handle linguistic-based linear and non-linear systems, and no mathematical model is required [18].

It is observed that the fuzzy logic system is more suitable and simple in solving DSM and so the Fuzzy logic controller is adopted in the proposed system. A simple and efficient fuzzy logic controller based DSM is developed to operate the loads in the appropriate time without sacrificing the sophistication of the consumer. The rest of the paper is arranged as follows: followed by the introduction part, the review of fuzzy logic control is explained. The proposed approach for demand response is explained in section 3 and section 4 elaborates on the development of the proposed FLC for DR. Section 5 renders the details about simulation details. Finally, this paper is concluded in section 6.

II. REVIEW OF FUZZY LOGIC

Fuzzy logic is derived from the fuzzy set theory of reasoning, which is approximate rather than precisely deduced from classical predicate logic. The fuzzy set theory offers an excellent way of expressing ambiguity because of vagueness in a system's available data or unexplained behavior. This can reflect the processes of human control, also can enable experimental knowledge to change the controller parameters. All real-valued input data is first fuzzified with statically defined membership functions. A membership function assigns a value of 0 to 1 for each point in the domain of the Fuzzy set. First, the idea behind the fuzzy logic control is to state the input parameters in natural language and, define the relationship between different inputs and the output with the aid of a fuzzy-rule collection. A set of rules are used to combine the input and output set to obtain the corresponding output of the status of the input. Thus the various steps followed by the fuzzy system are fuzzification of input variables, evaluation of rules, aggregation of the rule outputs, and defuzzification that is shown in Fig. 2 [19]. In Figure 2, the rules are framed from the knowledge of the outside world and specify how to react to input signals as well. The system continuously analyses the available inputs and makes rules-based decisions regarding system outputs.

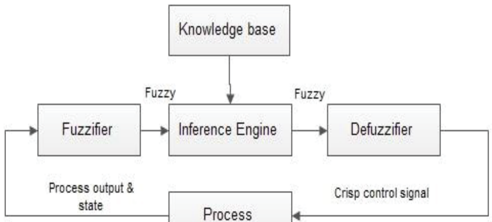

Fig. 2 Conceptual diagram of fuzzy logic

III. PROPOSED APPROACH FOR DR

To overcome the above-mentioned issues, a new concept based on fuzzy logic for demand-side load management in residential buildings is utilized. Here, the power usage during peak load hours is restricted by cutting some loads depending on cost and need. The same loads would be transferred to some other period, especially the non-peak period. The proposed CSM is designed using the Fuzzy Logic Toolbox. The various steps followed by the fuzzy system are fuzzification of input variables, the formation of rules, and aggregation of the rule outputs, and defuzzification, which is shown in Fig. 2. The rules framed here are based on outside world knowledge and specify how input signals can also be responded to the changes. The system analyzes the available inputs continuously and decides on system outputs based on rules.

Strictly speaking, 58 rules are framed based on if-then rules and given as knowledge base of Fuzzy Logic Controller. The very popular linguistic approach proposed by Mamdani is adopted due to its less complexity to design the Fuzzy Logic Controller (FLC). The rules are framed with five input parameters and two output parameters. The input parameters are time slots of 24 hours for load demand, Real-Time Price (RTP) obtained through Smart metering architecture, power ratings of the home appliance, Duration of the appliances operating period, and preferable operating hours of the home appliances. The home appliances considered in the proposed work are Washing Machine, Motor, Grinder, and Iron Box. The output parameters are the ON and OFF condition of the home appliances. Time slots are categorized between 0 to 24 hrs, the bidding cost is limited between ₹.0 to ₹ 2 based on the prerecorded bidding values. Power ratings are classified between 100W to 2000W based on the usage of home appliances. The output parameters are ON and OFF state and it is represented by 0 and 1.

In Table 1, the preferable condition for switching ON the home appliances is described. Based on the usage of load by the consumer, the 24 hours are categorized as very low peak time, low peak time, peak time, and critical peak time. Based on the categorization of the period, the Real-Time Pricing is fixed as very low, low, medium, high, and very high. The power rating of each load is labeled as a low, medium, and high wattage level. The operating hours for each load are classified as low medium and high. The preferable time-period for operating each load is classified based on consumer comfortability.

TABLE 1 UTILIZATION OF HOME APPLIANCES

Categorization of Time slot	Bidding cost (₹)	Power rating (Watt)	Duration of operating hours (Hr.)	Preferable/ non-preferable time	Home appliances (ON/OFF)
Very low Peak time 24.00 -06.00	₹ 0- ₹ 0.25 Very low	100-500W Low	0-1/2 Hr. Low	Morning 10.00-12.00 Afternoon 14.00-16.00 Evening 19.00-21.00	Washing Machine ON-1 OFF-0
Peak time 06.00-12.00	₹ 0.25- ₹ 0.50 Low	500-1000W Medium	1/2 – 1 Hr. Medium	Morning 6.00-8.00 Evening 17.00-19.00	Motor ON-1 OFF-0
Low Peak time 12.00 -17.00	₹ 0.50- ₹ 1 Medium	1000W - 1500W High	1-2 Hr. High	Morning 09.00-10.00 Evening 16.00-17.00 Night 18-19.00	Grinder ON-1 OFF-0
Critical peak time 17.00 -23.00	₹ 1- ₹ 1.50 High			Morning 08.00-09.00 After noon. 15.00-16.00 Night 21.00-22.00	Iron Box ON-1 OFF-0
	≥₹ 1.50 Very high				

IV. DEVELOPMENT OF FLC FOR DR

To design the FLC, the following decisions need to be identified properly.

- Selection of input and output of the Fuzzy logic controller
- Membership functions
- Fuzzy rule base formation.

4.1. System Design and Input-Output Parameters

The suggested fuzzy logic controller has five inputs: They are time slices, bidding price, power rating, and total operating hours of the individual loads per day and preferable and non-preferable load time slots. The two outputs are ON and OFF conditions of the loads. Figure 3 describes the schematic representation of FLC.

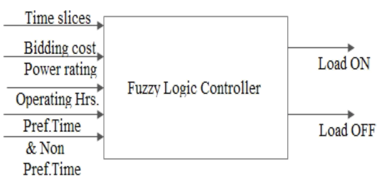

Fig. - 3 *Schematic representation of FLC*

This work proposes a fuzzy logic controller based Demand Side Management system. In this proposed strategy, four different home appliances (schedulable loads) with different power consuming capacity and allowable operating periods are taken into consideration. 24 hours of a day is divided into four-time slots as very low peak, low peak time, peak time, and critical peak time. Table 1 shows the categorization of inputs and outputs of the fuzzy logic controller. Consumer comfortability, cost, and demand responses are the three-optimization variables taken into account for the design of a fuzzy-based load management scheduler. The preset priority is predicated based on user behavior.

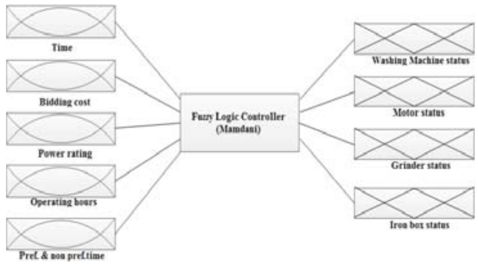

Fig. 4 - Schematic representation of the fuzzy input and output variables

Figure 4 depicts the schematic representation of the fuzzy input and output variables. Since the objective of the system is automatically participating in DR to conserve energy and load management, a fuzzy logic concept is assumed to be embedded with the existing Smart meter. Figures 4a to 4f represent the input and output membership function plots developed using a fuzzy toolbox.

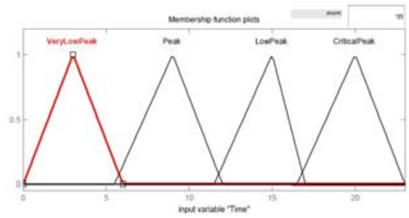

Fig.4a Membership Function of Input Variable-Time

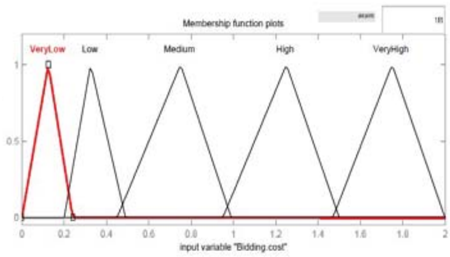

Fig.4b Membership Function of Input Variable-Bidding Cost

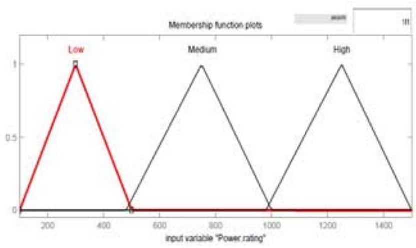

Fig.4c Membership Function of Input Variable-Power Rating

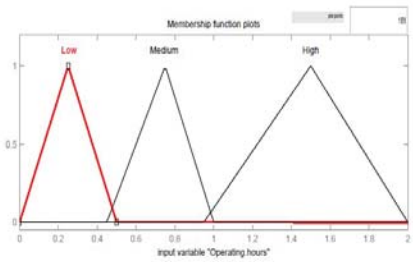

Fig. 4d Membership Function of Input Variable-Operating Hours

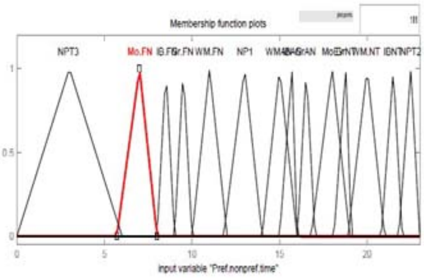

Fig. 4e Membership Function of Input Variable- Pref. Time

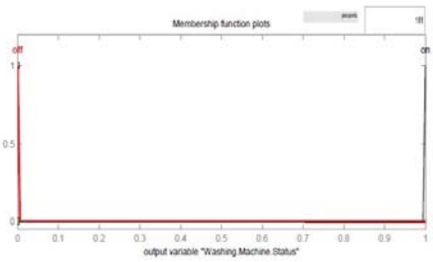

Fig. 4f Membership Function of Output Variable-Load ON

Triangular membership functions are selected for all input and output variables to define linguistic rules that govern the relationships between them. The degree of membership indicates the amount of the variable's participation in the Fuzzy Set. Fuzzy rule estimation occurs when the system takes fuzzified inputs and applies them to the antecedents of the Fuzzy rules. It is then applied to the corresponding membership functions. Using the rule-based structure of Fuzzy logic, a set of if-then statements has been framed.

Fuzzy rules are a vital part of the entire Fuzzy Logic Controller design. The number of ruleset depends on the number of membership functions found in the input and output frames. The number of rules will determine the performance and reliability of the Fuzzy Logic Controller. The developed FLC has 58 rules, some of which are listed below.

1) If (Time is Peak) and (Bidding_cost is Very_Low) and (power_rating is not High) and (operating_Hours is not High) and (Pref_nonpref_time is WM_FN) then (WM_Status is on)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

2) If (Time is Peak) and (Bidding_cost is Low) and (power_rating is not High) and (operating_Hours is not High) and (Pref_nonpref_time is WM_FN) then (WM_Status is on)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

3) If (Time is Low_Peak) and (Bidding_cost is Very_Low) and (power_rating is not High) and (operating_Hours is not High) and (Pref_nonpref_time is WM_AN) then (WM_Status is on)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

4) If (Time is Low_Peak) and (Bidding_cost is Low) and (power_rating is not High) and (operating_Hours is not High) and (Pref_nonpref_time is WM_AN) then (WM_Status is on)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

5) If (Time is Critical_Peak) and (Bidding_cost is Very_Low) and (power_rating is not High) and (operating_Hours is not High) and (Pref_nonpref_time is WM_night) then (WM_Status is on)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

6) If (Time is Critical_Peak) and (Bidding_cost is Low) and (power_rating is not High) and (operating_Hours is not High) and (Pref_nonpref_time is WM_night) then (WM_Status is on)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

7) If (Time is Very_Low_Peak) or (Bidding_cost is Medium) or (power_rating is High) or (operating_Hours is High) or (Pref_nonpref_time is NP1) then (WM_Status is off)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

8) If (Time is Very_Low_Peak) or (Bidding_cost is High) or (power_rating is High) or (operating_Hours is High) or (Pref_nonpref_time is NP1) then (WM_Status is off)(Motor_Status is off)(Grinder_Status is off)(IB_status is off) (1)

Tables 2 shows the membership function and limits of each input and output parameter respectively. The triangular membership function is commonly used for all input functions for its flexibility.

TABLE 2 MEMBERSHIP FUNCTIONS OF INPUT AND OUTPUT PARAMETERS

Parameters	**Category**	**Term set**	**Membership function**	**Limits (Periods)**
Input Para-meters	Categorization of Time slot	Very low Peak time 24.00-06.00	Triangular function	[0 3 6]
		Peak time 06.00 -12.00	Triangular function	[6 9 12]
		Low Peak time 12.00 -17.00	Triangular function	[12 15 17]
		Critical peak time 17.00- 23.00	Triangular function	[17 20 23]
	Bidding cost	Very low 0- 0.25	Triangular function	[0 0.125 0.24]
		Low ₹ 0.25-₹ 0.50	Triangular function	[0.25 0.325 0.49]
		Medium ₹ 0.50-₹ 1	Triangular function	[0.5 0.75 0.99]
		High ₹ 1-₹ 1.50	Triangular function	[1 1.25 1.5]
		Very high ≥₹ 1.50	Triangular function	[1.5 1.75 2]
		Low	Triangular	[100 300

	Power rating (Watt)	100-500W	function	500]
		Medium 500-1000W	Triangular function	[500 750 1000]
		High 1000W-1500W	Triangular function	[1000. 1250 1500]
	Duration of operating hours (Hr.)	Low 0-1/2 Hr.	Triangular function	[0 0.25 0.5]
		Medium 1/2 – 1 Hr.	Triangular function	[0.5 0.75 1]
		High 1-2 Hr.	Triangular function	[1 1.5 2]
	Preferable/ non-preferable time	Morning 10.00-12.00 Afternoon14.00-16.00 Evening19.00-21.00 Washing Machine	Triangular function	[10 11 12] [14 15 16] [19 20 21]
		Morning 6.00-8.00 Evening 17.00-19.00 Motor	Triangular function	[6 7 8] [17 18 19]
		Morning 09.00-10.00 Evening 16.00-17.00 Night 18-19.00 Grinder	Triangular function	[9 9.5 10] [16 16.5 17] [1818.5 19]
		Morning 08.00-09.00 Afternoon 15.00-16.00 Night 21.00-22.00 Iron-box	Triangular function	[88.59] [15 15.5 16] [21 21.5 22]
Output Parameters	Washing Machine	ON-1 OFF-0	Triangular function	[1 1 1] [0 0 0]
	Motor	ON-1 OFF-0	Triangular function	[1 1 1] [0 0 0]
	Grinder	ON-1 OFF-0	Triangular function	[1 1 1] [0 0 0]
	Iron Box	ON-1 OFF-0	Triangular function	[1 1 1] [0 0 0]

V. Results and Discussion

To analyze the performance of the proposed DSM, the structure is developed by the MATLAB Simulink toolbox. Here, the input parameters of FLC are obtained through constant nodes. These nodes are connected to FLC through Multiplexer. The Demultiplexer is used to divide the outputs, in which LEDs are connected to display the results. In this proposed work, few cases are considered for the validation of the developed DSM Model. The details of the few cases are given below.

Case 1(a): State of Washing Machine at Peak Time

The preferable times for operating the Washing Machine are Morning: 10.00-12.00, Afternoon: 14.00-16.00 and Evening: 19.00-21.00. In case 1, two preferable times 11.00 and 14.00 are taken for validation.

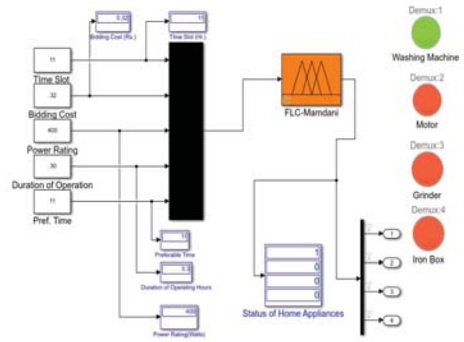

Fig. 5a. Simulink Model of Washing Machine Status at Peak Time

In the above Simulink model fig 5a, the chosen time slot is 11 AM, the received RTP for the mentioned hour is ₹ 0.32, which varies between ₹ 0.25 to 0.5. Since the selected power rating of the load is 400W and the preferable operating hours is about 30 minutes, the Washing Machine is Turned ON and the remaining loads are under OFF status.

Case 1(b): State of Washing Machine at Low Peak Time

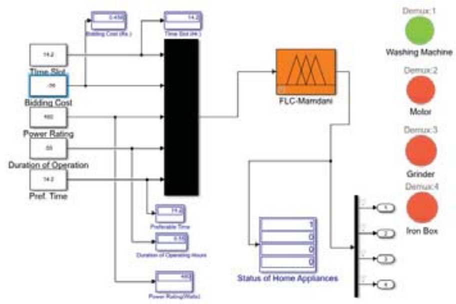

Figure 5b Simulink Model of Washing Machine Status at Low Peak Time

In the above Simulink model fig 5b, the chosen time slot is 14.2, the received RTP for the mentioned hour is ₹ 0.56, which varies between ₹ 0.5 to 1. Since the selected power rating of the load is 480W and the preferable operating hours is about 55 minutes, the Washing Machine is Turned ON and the remaining loads are under OFF status.

Case 2: State of Motor

The preferable times for operating the Motor are Morning: 06.00-08.00, and Evening: 17.00-19.00. In case 2, one preferable period is considered for validation.

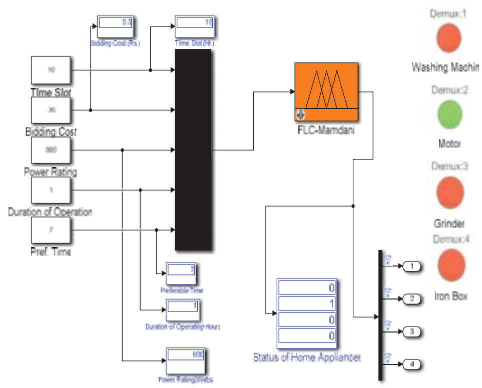

Figure 6 Simulink Model of Motor Status

Figure 6 shows the Simulink model for Motor ON State. In the above Simulink model, the preferable time slot is 7.00

AM, the RTP received for the corresponding time slot is ₹ 0.30. The consumer is preferred to use the loads in the range of 500W to 1000W in which 400W is chosen here and the operating hours of those loads must be operated about 30 minutes to 1 Hr, hence the MOTOR is Turned ON among the available loads and the remaining loads are under OFF status.

Case 3: Status of Grinder

The preferable times for operating the Grinder are Morning: 09.00-10.00, Evening: 16.00-17.00, and night: 18:00 – 19:00, out of three slots, 09.00 -10.00 is taken for validation.

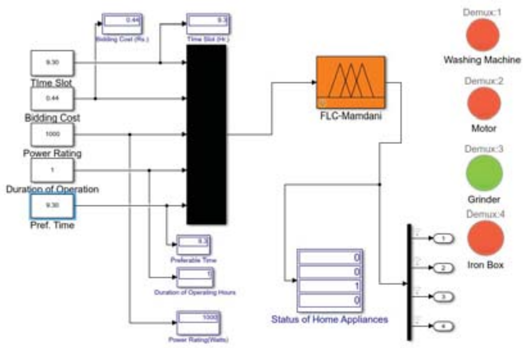

Figure 7 Simulink Model of Grinder Status

Figure 7 shows the Simulink model for Grinder ON State. In the above Simulink model, the preferable time slot is 9.30 AM, the RTP received for the corresponding time slot is Rs.0 .44. The consumer is preferred to use the loads in the range of 1000W to 1500W, in which 1000W is chosen here and the operating hours of these loads shall be around 1 Hr. In this state, the Grinder is Turned ON among the available loads and the remaining loads are under OFF status.

From the above analysis, it is inferred that the proposed model can give suggestions for the consumers to operate their loads at low RTP without compromising their comfortability.

VI.CONCLUSION

In this work, a fuzzy logic approach to facilitate participating in DR for the consumers whose energy bills is significantly related to their HVAC systems. The Fuzzy based DSM is developed and the data required for operating the DSM is fetched from the smart meter. The DSM is designed in Simulink and four different cases with four home appliances are validated. The developed CSM is used to give information to the consumers for operating their loads with the objective of low cost. The FLC based DSM performed well in different scenarios. The results show that the method significantly spread out the energy usage in residential buildings compared to existing methods because of the suggestions provided by the fuzzy approach. Besides, the system is capable of participating in DR automatically without any user interaction.

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