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B.J. LaMeres, M.H. Nehrir *, V. Gerez

Department of Electrical and Computer Engineering, College of Engineering, Montana State University, 610 Cobleigh Hall, Bozeman, MT 59717, USA

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Abstract

This paper describes a fuzzy logic-based control strategy for shifting the average power demand of residential electric water heaters. The proposed control strategy can shift the average power demand of residential electric water heaters from periods of high demand for electricity to off-peak periods. A minimum temperature for hot water, defined as customer comfort level, is used as a control variable. Water temperature is not allowed to fall below the minimum temperature set by the customer. Simulation results show that the proposed strategy can shift the average power demand of residential water heaters to improve the load factor of residential load profile. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Electric water heater; Power demand; Fuzzy logic

1. Introduction

Population growth along with technological growth force the utility companies to continue struggling to meet the ever increasing need for electricity. With the majority of residents conforming to the 08:00–17:00 work schedule, the utility companies experience overwhelming demand peaks associated with a large amount of power being consumed at the same time. Complementing this effect are periods of low demand. Although over a period of time, the average amount of power consumed by a community may be easily generated by a utility, that utility still has to provide enough generation to meet its highest power demand peak. As this trend continues, utility companies may inevitably adopt a real-time-pricing strategy, where customers will pay more for the electric power they use during high demand periods and less during low demand periods. It is in the best interest of the utility companies as well as the consumer to try to reduce these high peak demand periods and level out their power demand profiles as much as possible.

One way this can be accomplished is by controlling residential electric water heaters. The electric water heater accounts for the single largest contributor to the total power consumption of a residence. Fig. 1 shows the average daily total power demand and electric water heater power demand of a residence in the northwestern US, as reported in [1]. It is noted from this figure that the shape of the electric water heater demand curve follows closely that of total demand. This makes the electric water heater an ideal candidate for customer or utility demand-side management (DSM) to shift part of the utility power demand from peak demand periods to off-peak periods [4,6,7]. Such DSM strategies could be effective in utility peak load shaving and valley filling and therefore increasing the utility load factor. For this reason, electric water heaters have been the focus of many load analysis and demand-side management studies, i.e. [2,3,8,9].

Existing electric water heater DSM strategies focus on on/off control of the water heater, where a group of heaters are disabled during certain periods of time using a direct load control strategy [5]. When water heaters are energized, they are either on consuming a fixed amount of power, i.e. 4.5 kW, or they are off.

This paper presents a fuzzy logic-based variable power control strategy, where the power consumed by

* Corresponding author.
E-mail address: hashemn@ee.montana.edu (M.H. Nehrir)

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the water heater can be controlled based on the information available from the water heater such as water temperature, maximum and minimum water temperatures allowed (or desired) and distribution level power demand. Based on the status of the above variables, the fuzzy controller will determine the percentage of the maximum allowable power that the water heater should consume. Based on this information, a control signal is generated to control the voltage applied to the water heater.

The proposed control strategy will shift the average residential electric water heater demand curve so that its peak demand periods occur during the periods where the total utility power demand is low and vice versa. The fuzzy controller, which can be loaded on a microprocessor chip and installed on the water heater, can be tuned interactively by the customer or be controlled directly by the utility [11] for those customers who participate in such DSM strategy. Simulation results indicate that the use of the proposed fuzzy DSM strategy can result in a more flat utility demand curve and hence improve the utility load factor.

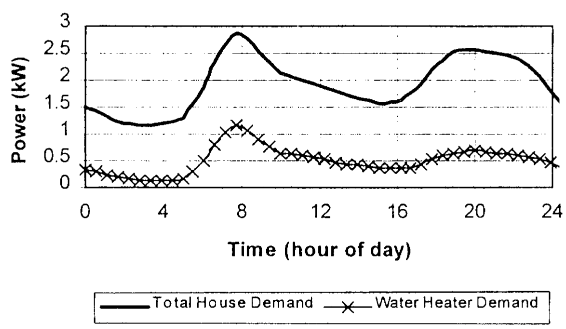

Fig. 1. Average residential daily total demand and water heater demand [1].

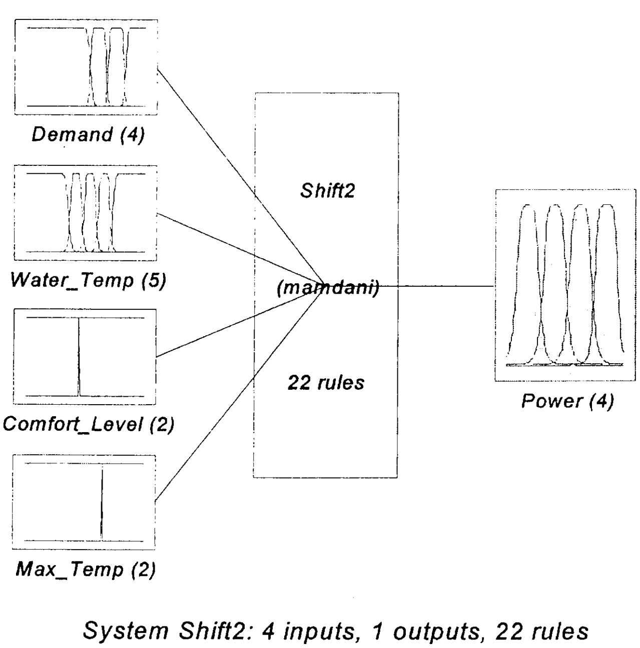

Fig. 2. Block diagram for the fuzzy logic controller.

2. Fuzzy logic-based electric water heater controller

Fuzzy logic control is a simple control strategy which works well for control of certain class of nonlinear systems that contain variables with uncertainty. This control strategy is suited well for control of electric water heaters, which exhibit non-linearity between the power consumed by the water heater and the water temperature [8,10] as well as exhibiting uncertainty in the hot water usage and temperature profile. Fig. 2 shows the block diagram for the proposed fuzzy controller. The input variables to the controller are:

1. Demand: Average residential electric water heater power demand as shown in Fig. 1.
2. Water_Temp: Temperature of the hot water at any given time.
3. Comfort_level: A minimum temperature for hot water, set by the customer. Water temperature is not to fall below this value. This temperature is set at 95°F in this study.
4. Max_Temp: Maximum water temperature allowed. This temperature is set at 130°F in this study.

The controller takes the four crisp input values, fuzzifies them, assigns a fuzzified control signal to control the voltage applied to the water heater based on the assigned rules and membership functions. The control signal is then converted to a crisp signal through defuzzification process [12]. The decision making process is based on a set of linguistic rules that will map each input signal to a set of membership functions that correspond to that input. These signals are, in turn, mapped to an output signal which will be proportional to the voltage which is to be applied to the water heater. As a result, the amount of power the water heater is allowed to consume at any given time will be controlled. Assuming water heater's heating element is purely resistive, its power consumption is proportional to the square of its voltage. Therefore, the water heater's power consumption becomes variable.

The proposed fuzzy controller was designed using 22 rules. The fuzzy membership functions and rules will be explained in the next two sections.

3. Membership functions

Fuzzy membership functions are needed for all input variables and the output variable in order to define linguistic rules that govern the relationships between them. Gaussian (bell-shape) membership functions were used for the input variables demand and temperature and the output signal (power) as they resulted in a

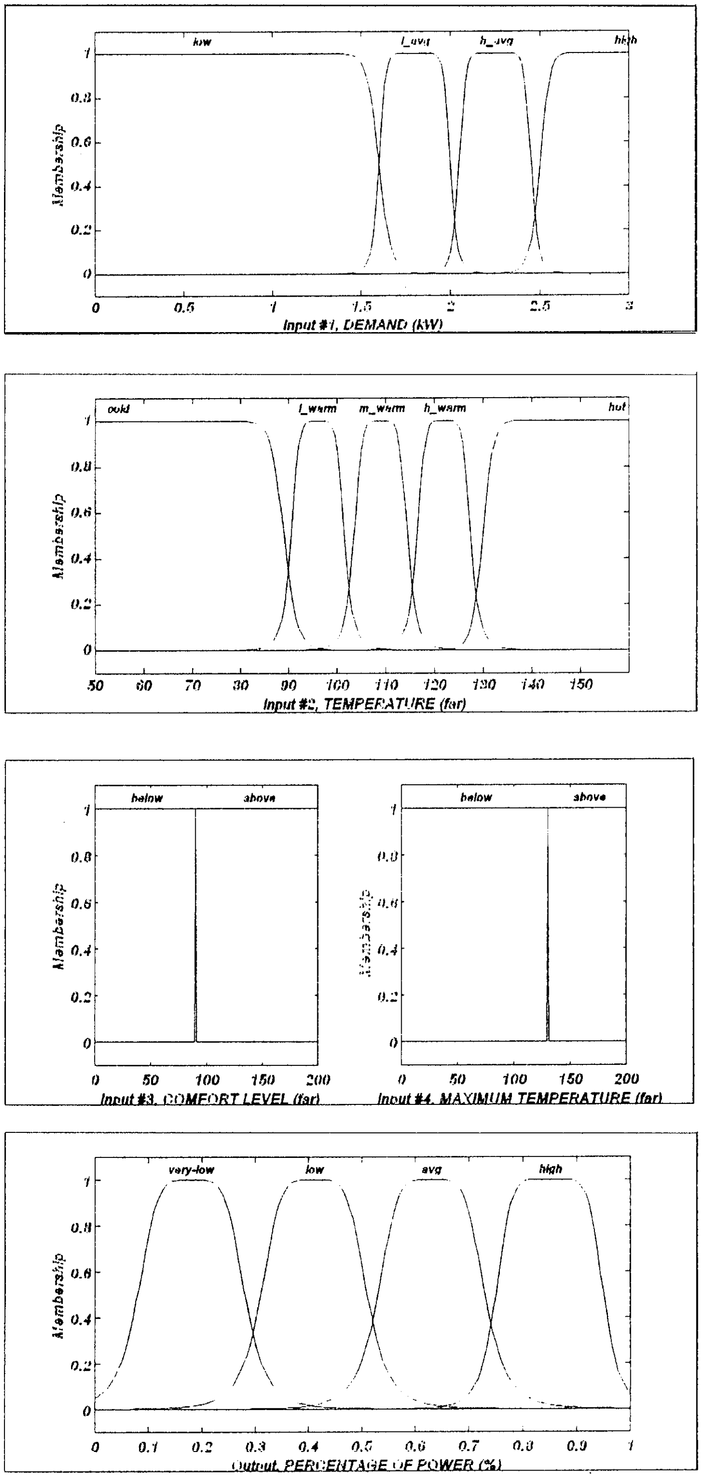

Fig. 3. Membership functions for the fuzzy logic controller.

smooth shifted water heater demand profile. On the other hand, sharp membership functions were chosen for the input variables, comfort level and maximum temperature because of the sharp constraints on those variables. Water temperature shall not drop below the comfort level and shall not exceed the maximum temperature assigned by the customer. The range for the membership functions were chosen based on experience. Fig. 3 shows the shape, range and the linguistic terms used for the input and output variables.

4. Fuzzy rules

A very important task in fuzzy controller design is the development of fuzzy rules for the problem at hand. The development of these rules depends in large on the experience and knowledge of the designer about the system. In the present case, the fuzzy controller is to shift the peaks of the water heater demand profile to periods where total demand, as seen by the utility, is low. At the same time, constraints set by the customer, i.e. the maximum and minimum temperatures for the hot water, should be met. A smooth shifted water heater demand profile was obtained (taking into account the constraints on the maximum and minimum water temperature) using 22 rules, as given below.

1. If (Demand is low) and (Water_Temp is cold) then (Power is high)
2. If (Demand is low) and (Water_Temp is l_warm) then (Power is high)
3. If (Demand is low) and (Water_Temp is m_warm) then (Power is avg)
4. If (Demand is low) and (Water_Temp is h_warm) then (Power is avg)
5. If (Demand is low) and (Water_Temp is hot) then (Power is low)
6. If (Demand is l_avg) and (Water_Temp is cold) then (Power is avg)
7. If (Demand is l_avg) and (Water_Temp is l_warm) then (Power is avg)
8. If (Demand is l_avg) and (Water_Temp is m_warm) then (Power is avg)
9. If (Demand is l_avg) and (Water_Temp is h_warm) then (Power is low)
10. If (Demand is l_avg) and (Water_Temp is hot) then (Power is very-low)
11. If (Demand is h_avg) and (Water_Temp is cold) then (Power is low)
12. If (Demand is h_avg) and (Water Temp is l_warm) then (Power is low)
13. If (Demand is h_avg) and (Water_Temp is m_warm) then (Power is low)
14. If (Demand is h_avg) and (Water_Temp is h_warm) then (Power is very-low)
15. If (Demand is h_avg) and (Water Temp is hot) then (Power is very-low)
16. If (Demand is high) and (Water Temp is cold) then (Power is very-low)
17. If (Demand is high) and (Water_Temp is l_warm) then (Power is very-low)
18. If (Demand is high) and (Water_Temp is m warm) then (Power is very-low)
19. If (Demand is high) and (Water_Temp is h warm) then (Power is very-low)
20. If (Demand is high) and (Water_Temp is hot) then (Power is very-low)
21. If (Max_Temp is above) then (Power is very-low)
22. If (Comfort_Level is below) then (Power is high)

Rules 21 and 22 set the boundaries for the maximum and minimum temperature, respectively. Note that in this study we have assumed that the temperature cannot exceed a certain limit. Therefore, there is a limit on the amount of power which can be applied to the water heater in order to heat the water during the periods where demand for electricity is low. Otherwise, water temperature will exceed its maximum limit. Similarly, water temperature should not fall below a minimum value set by the customer. Therefore, it may not be possible to reduce the power supplied to the heater all the way to zero during periods of high demand for electricity.

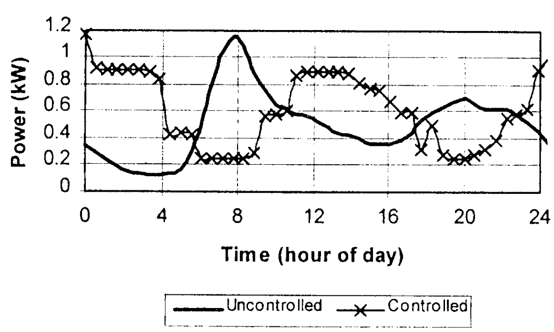

Fig. 4. Controlled and uncontrolled water heater demand.

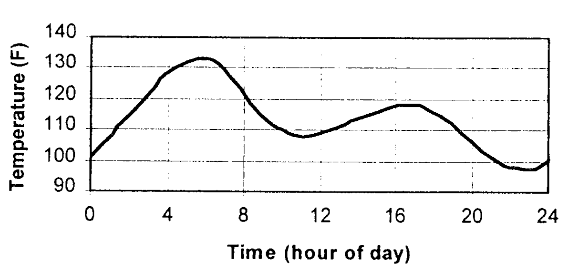

Fig. 5. Controlled water heater temperature profile.

5. Simulation results

Simulation studies were conducted to evaluate the effectiveness of the fuzzy controller to shift the average daily residential electric water heater power demand using the membership functions and rules given in the previous two sections. Fig. 4 shows a comparison of the fuzzy-controlled and uncontrolled water heater power demand. It is clear from this figure that under fuzzy control a large percentage of the water heater power demand has been shifted from periods of high demand for electricity to off-peak periods.

Fig. 5 shows the temperature profile of the hot water for a 24-h period when the water heater is under fuzzy control. Water temperature falls during periods of high

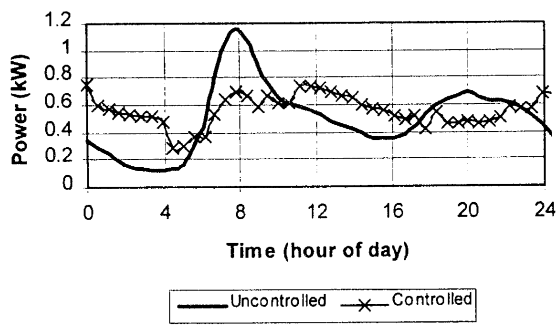

Fig. 6. Comparing average demand of one controlled and one uncontrolled water heater with two uncontrolled ones.

demand for electricity because of high usage of hot water and the fact that power supplied to the water heater is kept low during those periods. On the other hand, power supplied to the water heater is high during periods where demand for electricity is low and water temperature rises during these periods.

It should be noted that cooperation and some planning for the use of hot water is expected from the customers participating in the proposed fuzzy logic-based DSM strategy.

Fig. 6 shows the average power demand profile of one fuzzy-controlled and one uncontrolled water heater and the average power demand of two uncontrolled water heaters. It is clear from this figure that the load factor, defined by Eq. (1), is improved significantly for the average demand profile of one fuzzy-controlled and one uncontrolled water heater as compared to that for two uncontrolled water heaters.

$$\text{Load Factor} = \frac{\text{Avergage Demand}}{\text{Peak Demand}} \quad (1)$$

It is also noticed by comparing Figs 6 and 4 that the peak demand of average of one fuzzy-controlled and one uncontrolled water heater has been reduced as compared to that for all fuzzy-controlled water heaters, therefore indicating an improved load factor for the former.

6. Conclusions

In this paper a fuzzy logic-based demand-side management strategy was presented for controlling the average daily power demand of residential electric water heaters. The proposed DSM strategy is based on variable power consumption of the water heater by controlling its applied voltage. The fuzzy logic controller uses hot water temperature, distribution level demand and maximum and minimum allowed temperature for the hot water as input variables and outputs a decision signal which controls the magnitude of the input voltage to the water heater.

Simulation results show that it is possible to reduce the peaks of average residential water heater power demand profile and shift them from periods of high demand for electricity to low demand periods using the proposed customer-interactive DSM strategy. As a result, the load factor of the daily average residential power demand can be improved resulting in improved utility load factor. The proposed strategy can also be beneficial to the customers participating in such DSM programs, specially in a real-time pricing environment. Cooperation and some planning for use of hot water is necessary by the customers participating in such DSM programs.

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