A CUSTOMER-INTERACTIVE ELECTRIC WATER HEATER DEMAND-SIDE MANAGEMENT STRATEGY USING FUZZY LOGIC

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Abstract: This paper describes a fuzzy logic-based demand-side management (DSM) strategy to shift the peaks of the average residential electric water heater power demand profile from periods of high demand for electricity to off-peak hours. The DSM strategy is achieved by dividing the distribution area water heaters into several blocks and controlling each by a different fuzzy controller. Simulation results are presented to show the effectiveness of the proposed DSM strategy to shift the average electric water heater peak demand to off-peak periods and to level utility distribution demand profile.

Key Words: Electric water heater, fuzzy logic control, demand-side management

I. INTRODUCTION

A large percentage of residential water heaters are electric, and the power consumption of these water heaters accounts for about 30% of the their total residential power demand. Moreover, the average daily power demand profile of these heaters follow that of the average total daily residential demand, as shown in Fig. 1 [1]. Therefore, These loads are important contributors to the utility distribution peak power demand. This is particularly true in distribution substations that experience winter peaking demand. On the other hand, because water heaters have energy storage capability and can be easily controlled, they are ideal candidates for DSM studies to shift part of the utility power demand from peak demand periods to off-peak hours in order to level the utility demand profile [2]. For this reason, electric water heaters have been the focus of many load analysis and DSM studies [3-5].

Conventional residential electric water heaters consume a fixed amount of power, i.e. 4.5 kW. Conventional DSM strategies focus on block by block or random on-off control of the water heaters, where they are turned off during certain time periods through a direct load control strategy. This paper presents a multiple block fuzzy logic-based variable power control strategy to control the power consumed by the water heater. Considering the energy storage capability of water heaters, they do not have to heat water at their full rated power when hot water is being used. Their power consumption can be controlled to be anywhere between zero and their full capacity by controlling the voltage applied to their heating elements. In this study the residential electric water heaters of a distribution area are divided into several blocks and a different fuzzy logic controller controls the voltage applied to each group of water heaters. The controllers shift the peak power demand of each block to a different time period throughout the day where demand for electricity is low.

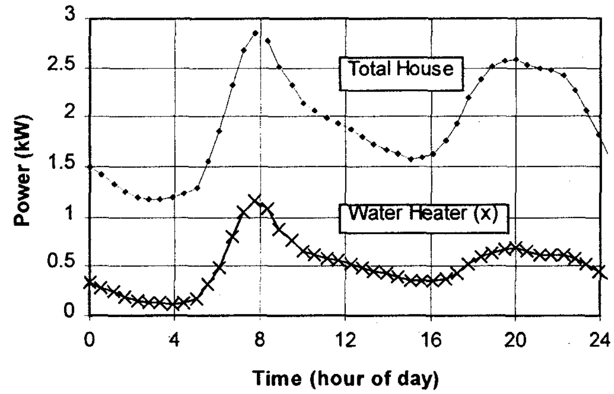

Fig. 1 Daily average Total residential demand and electric water heater demand [1].

The proposed water heater DSM strategies can be very useful in a real-time pricing environment or when other financial incentives are provided to the customers to encourage them to reduce electric power consumption during peak demand hours. Customers who are willing to adjust their life styles to let their hot water temperature slide down during peak demand hours and shift a percentage of their water heater power consumption to off-peak periods can have better savings. The fuzzy controller can be loaded on a microprocessor chip, installed on the water heater, and be controlled directly by the utility for those customers who participate in such DSM strategy [6]. The details of electric water heater model development are given in [7].

Simulation results are presented to support the feasibility of the application of the proposed DSM strategy for leveling utility demand profile.

II. FUZZY CONTROLLED VARIABLE POWER WATER HEATER

Power consumed by the resistive heating elements of electric water heaters is directly proportional to the square of the voltage applied to those elements. Therefore, water heater power consumption can be controlled by controlling the magnitude of the voltage applied to the water heater. When possible, it is desired to keep the magnitude of the applied voltage to the water heater low during peak demand periods and keep it high during low demand hours. This will shift the peak water heater demand to time periods where the average total residential demand is low (see Fig.1). The block diagram for the proposed variable voltage/power electric water heater is shown in Fig.2. The signal controlling the magnitude of the voltage applied to the water heater is a function of four inputs to the fuzzy controller: The temperature of the hot water in the water heater tank, utility power demand, and customers' preferences designated by the maximum and minimum temperatures for the hot water. In the fuzzy decision making process, the above four crisp inputs are fuzzified, and based on a set of linguistic rules, an output signal is determined to control the magnitude of the voltage applied to the water heater. The fuzzy rules and membership functions for the input and output variables, which govern the operation of the fuzzy control strategy, are given in the next two sections.

III. FUZZY MEMBERSHIP FUNCTIONS AND RULES

Fuzzy membership functions are needed for all input and output variables in order to define linguistic rules that govern the relationships between them. Gaussian (bell-shape) membership functions were found to be most suitable for the fuzzy controller inputs, demand and temperature (of hot water), and the output signal (power). On the other hand, sharp membership functions were chosen for the desired maximum temperature and minimum temperature (comfort level) because of the sharp constraints on those variables. Water temperature shall not drop below the comfort level and shall not exceed the maximum temperature designated by the customer. Fig. 3 shows the shape, range, and the linguistic terms used for the membership functions.

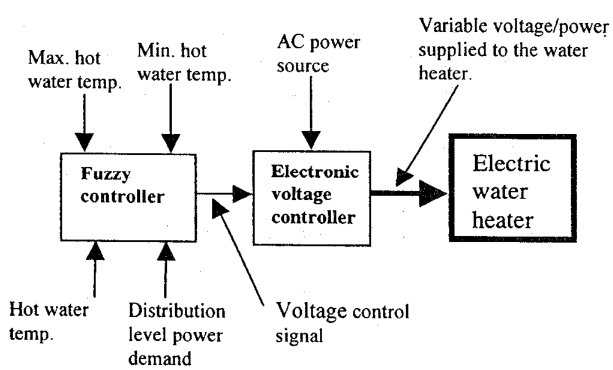

Fig.2 Fuzzy-controlled electric water heater block diagram.

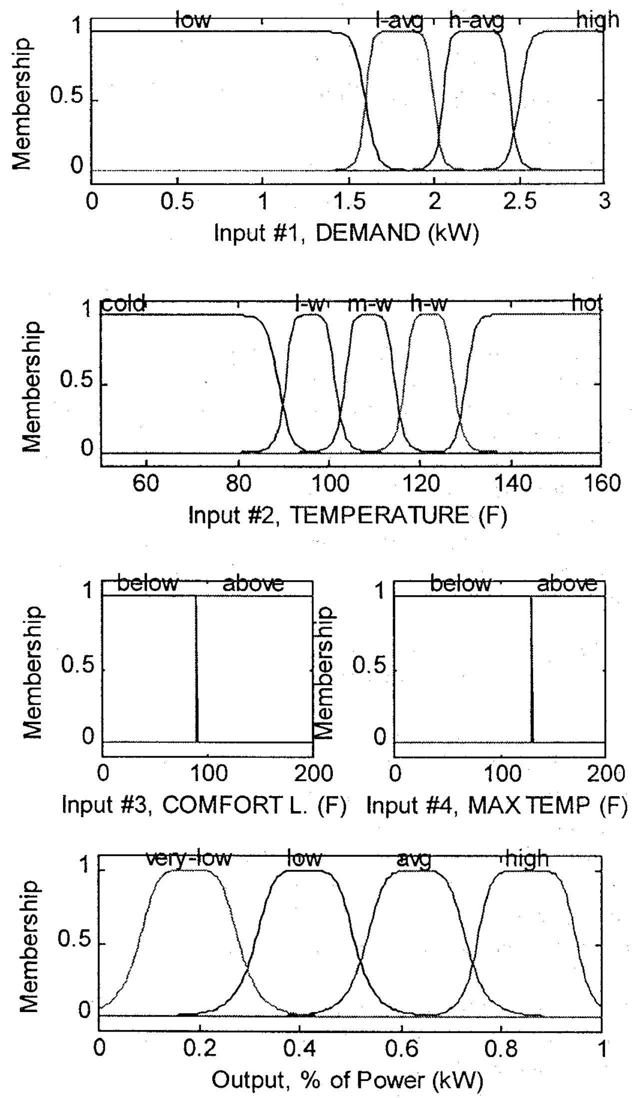

Fig. 3 Fuzzy membership functions.

IV. SHIFTING WATER HEATER POWER DEMAND BLOCK BY BLOCK

Using a single fuzzy controller to shift the total water heater peak demand to low demand periods may shift the peak(s) from one period to another without leveling the demand profile. This situation can be avoided by dividing the water heaters, fed from a distribution feeder, into several groups (blocks). A different fuzzy controller can be designed for each block to shift the peak demand for that block to a specified time interval during the feeder off-peak periods. For the purpose of this study the electric water heaters of a distribution area are divided into four blocks. Three of the blocks will have their demand peaks shifted to different times during low demand periods, while the fourth block will not have a fuzzy controller and its power demand profile will not be shifted. To distinguish the three controlled blocks, the low demand periods of the uncontrolled demand profile of Fig. 1

are divided into three regions depending on the slope of the total demand curve (see Fig. 1). 1) *Low demand*, represents the low demand regions of the total demand curve with slope near zero, 2) *Low-Rising*, represents the low demand regions with positive slope, and 3) *Low-Falling*, represents the low demand regions with negative slope. By shifting the demand peaks of each block of water heaters to one of the above regions, the overall average of four blocks (three controlled blocks and one uncontrolled block) is expected to be a more level curve as compared to when a single fuzzy controller is used to control all the water heaters in the distribution area.

Fig. 4 shows the block diagram for the proposed block by block shifting strategy using three fuzzy logic controllers. The general block diagram for each fuzzy controller is similar to that given in Fig. 2.

In the block by block DSM strategy, the upper temperature limit for hot water is raised to 180 °F to make the most use of the available power during off-peak periods to heat water. Under normal conditions, water temperature does not reach this upper limit. However, it is assumed that hot water will be mixed with cold water immediately after getting out of the water heater tank (before flowing out of any faucet) if water temperature exceeds a certain limit. This assumption is made in order to prevent flow of burning hot water out of any faucet that can be unsafe to the customer.

Membership functions for the input variables (demand, water temperature, maximum and minimum water temperature allowed) and for the output variable (percentage of power) for each fuzzy controller are the same as those shown in Fig. 3. The extra input to each fuzzy controller is a Boolean flag that indicates whether the power demand in the low demand region of the power demand profile is rising or falling. The flag will be '0' when the power profile is falling and '1' when it is rising. This information is obtained by comparing the current and previous values of the power demand at each sample point. It is to be noted that in order to obtain correct information about the rising/falling status of the demand profile, it is assumed that a smooth power demand profile, like that shown in Fig. 1, is used.

V. SIMULATION RESULTS

The distribution area water heaters are divided into four blocks as explained earlier. The water heater demand profile of the average uncontrolled house (shown in Fig. 1) is considered as the average residential water heater demand profile for each block. Peak power demand for three of the blocks are shifted to different time periods (*low, low-rising,* and *low-falling*), as shown in Fig. 1. The average demand profile of the fourth block of water heaters is kept uncontrolled (not shifted). Water is heated during the time periods where excess power is available, but water heating is kept *low* during high demand hours unless necessary. For each block of water heaters, water is heated the most in one of the specified time periods, *low, low-rising,* or *low-falling*.

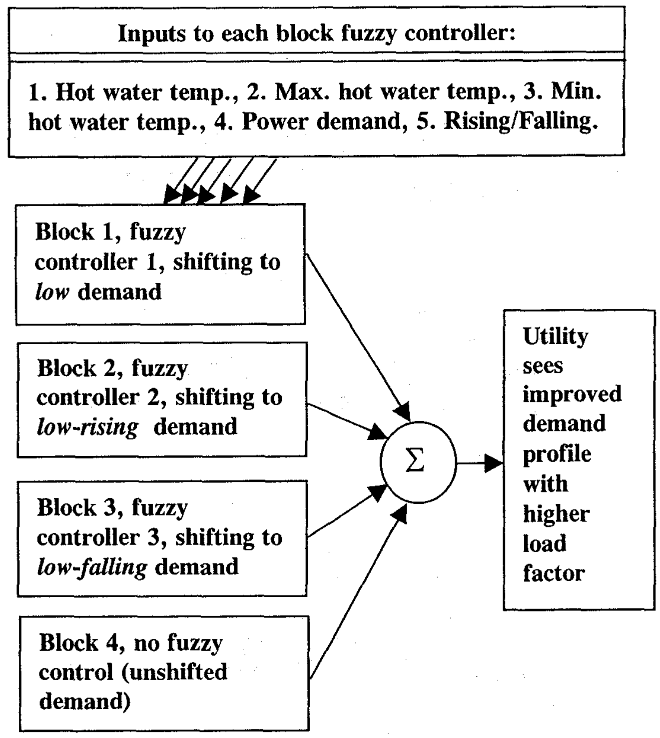

Fig.4. Block diagram for block by block water heater load shifting strategy.

Satisfactory control was achieved with only seven rules for each block's fuzzy controller. Fig. 5 shows the shifted (controlled) and uncontrolled demand profiles for the three controlled blocks. It is clear from this figure that the peaks of the water heater demand profile for each block have been shifted to the desired (specified) time periods, i.e. to low demand, low rising or low falling periods. Water temperature did not exceed 160 °F or fall below 95 °F for the average house water heater for any of the blocks. The hot water temperature profile for the first block (block 1, shifting to *low demand*) is shown in Fig. 6.

Fig. 7 shows the power demand profile of the average of four blocks of water heaters (with only three blocks being controlled) and that of the uncontrolled water heater. It is clear from this figure that the peaks of the controlled water heater demand profile have been reduced and shifted to low demand time periods. Therefore, the proposed multiple block fuzzy DSM strategy can be effective in leveling the distribution feeder demand profile and hence improving utility load factor.

VI. CONCLUSIONS

In this paper a customer-interactive fuzzy logic-based electric water heater DSM strategy was presented for leveling the power demand profile of a distribution area. It was accomplished by controlling the power consumption of the area water heaters to shift the peak water heater power

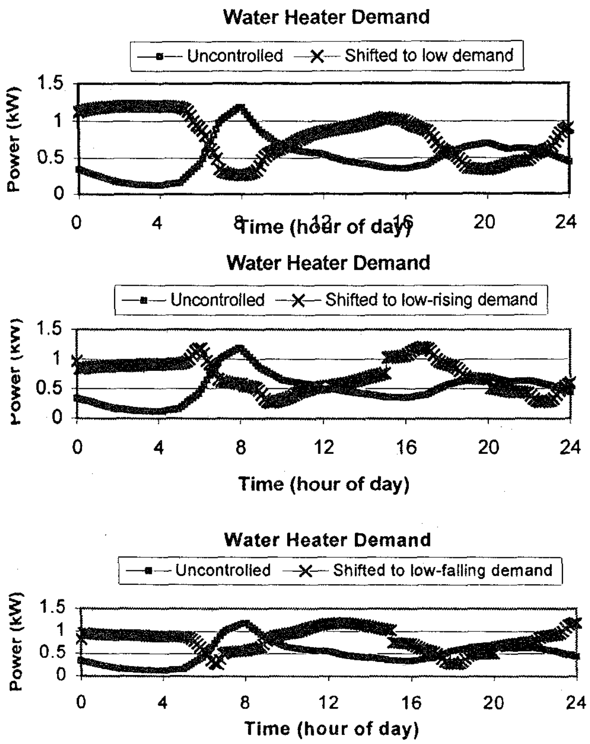

Fig. 5 Average water heater power demand profile shifted to three different time periods.

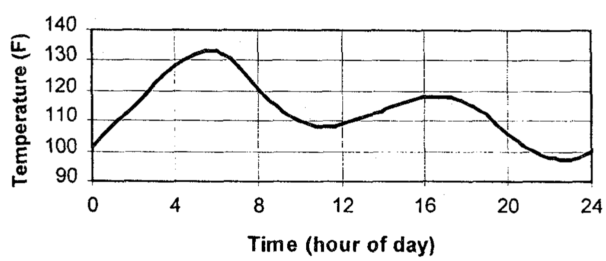

Fig. 6 Hot water heater temperature profile for the block shifted to periods of *low* demand.

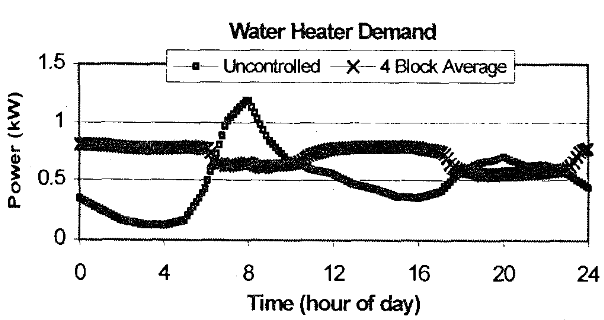

Fig. 7 Power demand profile for average of four blocks of water heaters with three blocks being controlled.

demand from the time periods where demand for electricity is high to off-peak hours. Water heaters in the distribution area were divided into blocks and the peak demands of each block were shifted to a different time period during which demand for electricity was *low, low-rising,* or *low-falling*. Simulation results show that the proposed DSM strategy is effective in leveling distribution system power demand profiles. It is to be noted that cooperation of the participating customers with the utility implementing the proposed DSM strategy is necessary. Therefore, the proposed strategy can be more effective when financial incentives, such as real-time pricing of electricity, are provided by the utility to encourage customer cooperation.

ACKNOWLEDGMENTS

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Biographies

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