SHIFTING RESIDENTIAL ELECTRIC THERMAL STORAGE LOADS: AN AUTOMATED FUZZY LOGIC- BASED CONTROL STRATEGY

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ABSTRACT

In this paper a methodology is presented for management of residential electric thermal storage loads, such as electric space heaters and water heaters, for shifting their electric power demand. An automated fuzzy logic-based control strategy is proposed for shifting the electric power demand of a residential water heater from periods of high demand for electricity to off-peak periods considering customer life style as a control variable. Simulation results are given for shifting the power demand of an average residential unit using the proposed water heater load shifting strategy.

KEYWORDS: Electric thermal storage load, electric water heater, load shifting, fuzzy logic

I. INTRODUCTION

Electricity can not be stored; it must first be converted to other forms of energy suitable for storage, such as thermal, chemical, and then be stored. Electric thermal storage (ETS) devices, such as electric water heaters and space heaters, convert the electric energy to thermal energy and store it in their available thermal storage capacity, i.e. as hot water stored in the water heater tank or as heat stored in the space heated by the space heater. The energy storage capability of such electric loads can be used in utility demand side management (DSM) to shift a part of the utility power demand from peak demand periods to off-peak periods [1].

Proper shifting of the power demand pattern of ETS loads can result in utility peak load shaving and valley filling, and therefore in improved load factor and deferment of generation capacity additions. In such applications the electricity produced during off-peak hours, when plenty of generating capacity is available, is converted to heat and stored in ETS devices for use during peak demand periods. The electric load shifting of the ETS devices on the customer side is very efficient and requires little investment by the utility. Such DSM strategies are specially effective in a real-time pricing environment.

To maximize the benefits of DSM strategies that use ETS devices, the use of an intelligent load shifting strategy for changing the power demand pattern of these devices is essential. The intelligent controller should continuously use information about the available electric power generation, the status of the ETS device used in DSM, and the cost of electricity (in a real-time pricing environment) and provide a decision signal to control the power demanded by the ETS loads.

This paper describes a methodology for the management of residential ETS loads, with a focus on residential electric water heaters, using a fuzzy logic-based controller which can be tuned interactively by the customers. For example, the customers can adjust their controllers based on the price they can afford (or are willing) to pay for the electricity they use to heat the water. In the United States, in the rural as well as urban areas, a large percentage of the residential water heaters are electric. These loads represent more than 30% of the total residential electric energy consumption. Moreover, the shape of the daily power demand of residential electric water heaters closely matches the total residential electric demand [2], i.e., the peaks and the valleys of the daily water heater demand curve and total residential demand curve occur at about the same time . Since water heaters can store energy, they do not have to operate at the same time hot water is being used [3-5]. Therefore, in most cases a part of the water heater power demand can be shifted to off-peak time periods, hence leveling the power demand profile.

An example on shifting the power demand of an average residential unit, using the proposed fuzzy logic based water heater load shifting strategy, is given in this paper.

II. VARIABLE POWER ETS

A customer-interactive ETS power controller is an electronic voltage controller which can be installed on the ETS devices. The customer can program the controller to limit the power demanded by the ETS during peak electric power demand periods and use maximum power during off-peak hours. The controller will control the heater power by controlling the voltage applied to its heating element. Assuming the resistance of the heating element of the ETS device (R) to be constant, the power consumed by R is proportional to the square of the voltage applied to the ETS heating element. Such a voltage controller can be implemented using available power electronic components. Fig. 1 shows a block diagram for the proposed variable voltage/power ETS, e.g., electric water heater or space heater.

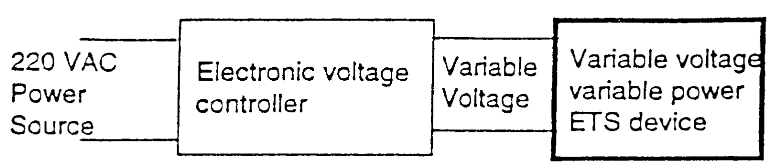

Figure 1. Variable power electric thermal storage.

The magnitude of the voltage applied to the ETS device at any given time depends on the customer's preferences (i.e. desired comfort or expenditure levels) and therefore willingness to shift the ETS power consumption pattern. For example, changing the power consumption pattern of a residential electric water heater depends on the customer's willingness to limit hot water usage during peak demand periods and also on the minimum temperature (for the hot water) set by the customer.

In the next section shifting the power consumption of a residential electric water heater using a customer interactive fuzzy controller will be discussed.

III. FUZZY CONTROLLED ELECTRIC WATER HEATER

Power supplied to a water heater participating in a DSM program can be controlled by controlling the voltage supplied to the water heater's heating element as shown in Fig. 1. This voltage is a function of several variables such as customer comfort level (a desired minimum temperature for the hot water), actual temperature of the hot water (available in the water heater tank), cost of energy, and the power demand at the distribution level. Therefore, the power supplied to the water heater can be controlled by controlling its voltage using the above variables. These variables, which can lead to uncertainty in decision making may be defined by fuzzy linguistic terms. Therefore, an intelligent fuzzy logic-based control strategy can be used to determine the control signal applied to the electronic voltage controller (shown in Fig. 1) to control the water heater power consumption. The block diagram for the proposed fuzzy-controlled electric water heater is given in Fig. 2.

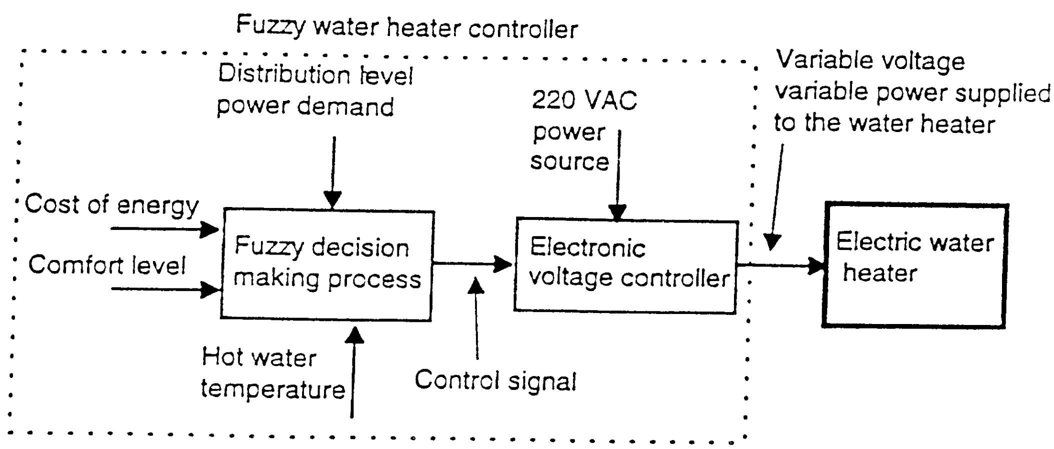

Figure 2. Proposed fuzzy water heater controller block diagram.

IV. AN EXAMPLE

In this example the average daily electric water heater power demand of an average home, taken from [2], is shifted so that the water heater peak demand periods are shifted to the periods where demand for electricity is low. For an average home, the daily electric water heater power demand profile follows the total daily demand curve of the average home and the daily aggregate power demand curve of a utility. These demand curves have a peak in the morning between 7 AM and 9 AM and another peak in the evening between 7 PM and 9 PM. Fig. 3 shows a comparison of the daily average water heater demand and the total demand of an average home [2].

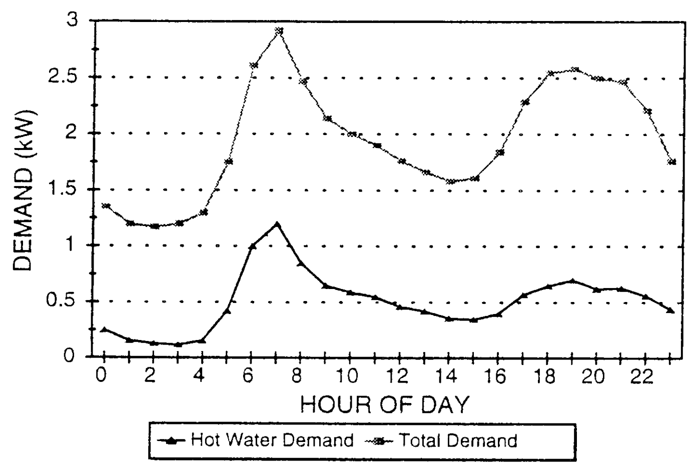

Figure 3. Average daily water heater demand and total demand of an average home [2].

To reduce the need for peak power generation, utilities would like to have their load profiles as flat as possible. Therefore, they like to see a part of the power demand from their system be shifted from high demand to off-peak periods. In this example the operation of a single residential water heater is controlled, using the proposed fuzzy logic-based control strategy, to shift the peak of the water heater power demand from periods of high power demand (at the distribution level) to low demand periods. Considering the power demand profiles shown in Fig. 3, it is desired to shift the peak water heater power demand occurring in the morning hours to noon or mid-afternoon hours. Similarly, it is desired to shift the peak occurring in the evening to late evening or after midnight (very early morning) hours. This has been done using the commonly used triangular shaped membership functions for the variables. Typical fuzzy rules for the proposed water heater load shifting are:

1) *If demand is low and water is cold, then heater power consumption is high.*
2) *If demand is average and water is cold, then heater power consumption is high.*
3) *If demand is low and water is warm, then heater power consumption is very high.*
4) *If demand is average and water is warm, then heater power consumption is high.*
5) *If demand is high and water is hot, then heater power consumption is low.*

Fig. 4 shows the simulation result for the proposed water heater load shifting. As shown, the morning peak of the average water heater demand of a single residential heater is shifted to noon and early afternoon, and its evening peak is shifted to late evening and very early morning hours, where the demand for electricity is low.

Fig. 5 shows the water temperature profile when the water heater power demand is shifted. As shown in this figure, power supplied to the water heater is set high so that water is heated (water temperature increases) during late evening hours and very early morning hours when demand for electricity is low. On the other hand, the water heater power consumption is limited to a minimum and water temperature keeps decreasing during morning and evening peak demand periods, but without falling below a pre-set temperature. A pre-set temperature of 85° F was used in this case.

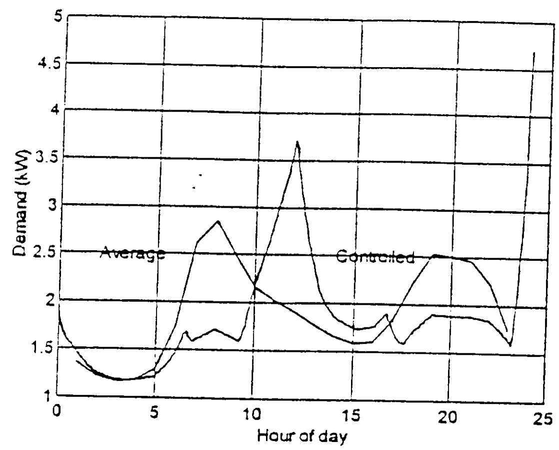

Figure 4. Average load vs. shifted load.

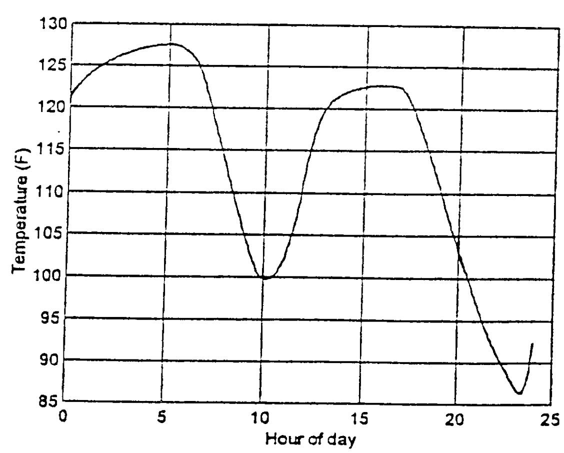

Figure 5. Hot water temperature profile for an electric water heater under load shifting.

V. DISTRIBUTION LEVEL LOAD MANAGEMENT

As seen in the previous section, the power consumption of each customer's water heater participating in automatic load shifting can be controlled to shift some of its power consumption from periods where demand for electricity is high to low demand periods.

Automated fuzzy logic-based water heater load shifting strategies also have the potential of leveling utility load profile at the distribution level. Under such load shifting strategy the power consumption of water heaters belonging to customers participating in the utility load management program will be kept to a minimum during periods of high demand and spread over the periods where demand for electricity is low. This will prevent a shift in the utility peak load from one time to another. Instead it will guarantee peak load shaving and valley filling, which will improve utility load factor and therefore its asset utilization. An example of a typical distribution feeder load profile and one after water heater load shifting is shown in Fig. 6.

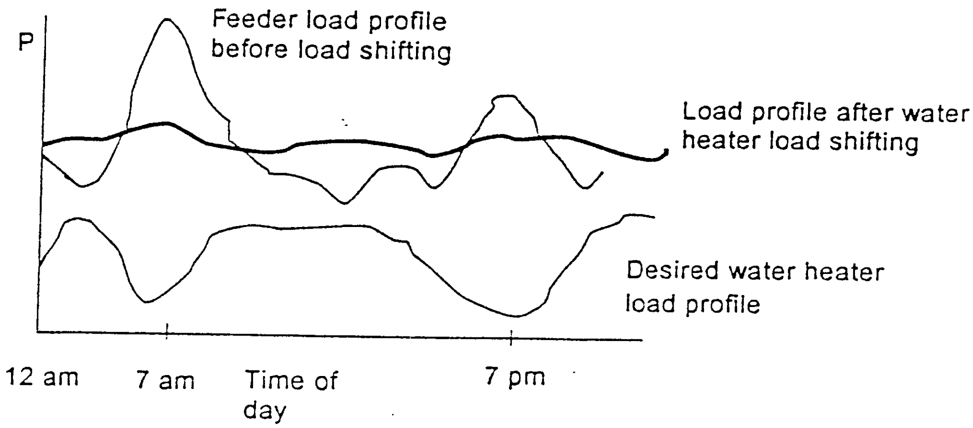

Figure 6. Distribution feeder load profile before and after load shifting.

VI. CONCLUSIONS

In this paper a fuzzy logic-based control strategy was presented for controlling the power consumption of a residential electric water heater. It was shown that water heater power consumption can be limited during the periods where electric power consumption is high and be shifted to periods where demand for electricity is low. A minimum temperature, below which water temperature is not allowed to fall, was used as the minimum comfort level acceptable to the customer. The proposed control strategy is based on the fact that water does not have to be heated at the same time hot water is being used. Therefore, customer cooperation is very essential. Implementation of the proposed load shifting strategy can result in significant savings for the customers participating in the program and can be extended for water heater demand side management at the utility distribution level.

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