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A multiple-block fuzzy logic-based electric water heater demand-side management strategy for leveling distribution feeder demand profile

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Abstract

This paper describes a multiple-block fuzzy logic-based demand-side management (DSM) strategy to shift the peaks of the residential electric water-heater power demand component of a distribution area from periods of high demand for electricity to off-peak hours. This is achieved by dividing the distribution area into several blocks and, controlling each block by a different fuzzy controller. Simulation results are presented to show the effectiveness of the proposed DSM strategy to shift the electric water-heater peak demand to off-peak periods and to level the utility distribution demand profile. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Electric water heater; Fuzzy logic control; Demand-side management

1. Introduction

A large percentage of residential water-heaters are electric, and the power consumption of these water-heaters accounts for about 30% of the 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 peak power demanded from a utility. This is particularly true in distribution sub-stations that experience winter peaking demand. On the other hand, water-heaters have energy storage capability and can be easily controlled, they are ideal candidates for demand-side management (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 [3–10].

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 water-heaters, where certain water-heaters are turned off during certain time periods through a direct load control strategy. However, considering the energy storage capability of water-heaters, they may not have to heat water at their full-rated power, when hot water is being used during peak demand periods. A water-heater power consumption can be controlled to be anywhere between zero and its full capacity by controlling the voltage applied to its heating element. In a real-time pricing environment, some customers may choose to control their water-heaters not to heat water at their full capacity during peak demand hours, if water temperature is higher than a certain minimum value (called the customer comfort level in this paper) set by the customer. In an earlier study [11], the authors have presented a single fuzzy logic-based voltage controller to control the magnitude of the voltage applied to the water-heater in order to shift the peak water-heater power consumption to low-demand periods. The fuzzy controller used the following input variables: temperature of hot water, utility

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power demand, and the maximum and minimum temperature for hot water acceptable to the customer, where the last two parameters could be set interactively by the customer.

This paper presents a multiple-block fuzzy logic-based water-heater DSM strategy, where the electric water-heaters fed by a distribution feeder are divided into several blocks, and the peak power demand of each block is shifted to a different time period throughout the day, where demand for electricity is low. This strategy will avoid the possibility of shifting the overall water-heater peak demand component of a distribution area to one point in time and will result in a more level utility demand profile and therefore higher load factor. The proposed DSM strategy can be useful when a financial incentive is 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 proposed fuzzy controller can be loaded on a microprocessor chip, installed on the water-heater, and be controlled directly by the customers, or the water-heaters may be controlled by the utility through direct load control for those customers who choose to participate in such DSM strategy [12]. Simulation results are presented to support the effectiveness of the proposed DSM strategy in leveling utility demand profile.

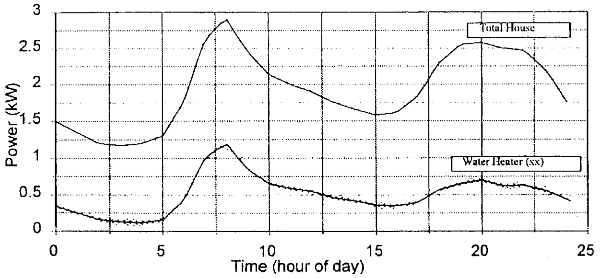

Fig. 1. Daily average, total residential demand and electric water-heater demand [1].

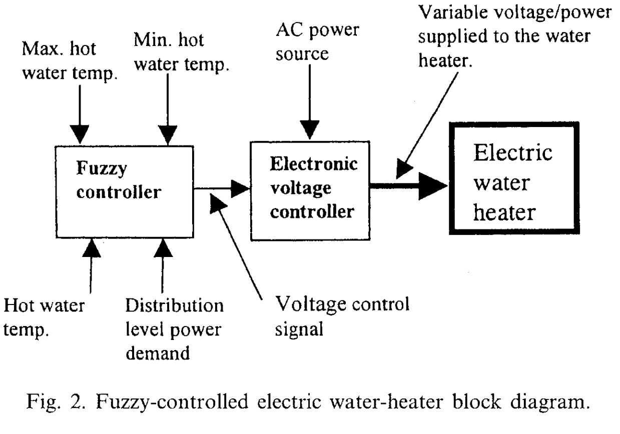

Fig. 2. Fuzzy-controlled electric water-heater block diagram.

2. Fuzzy controlled variable power water-heater

Power consumed by the resistive heating elements of electric water-heaters are directly proportional to the square of the voltage applied to those elements. Therefore, controlling the magnitude of the voltage applied to the water-heater can control the water-heater power consumption. 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: 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 an output signal is determined to control the magnitude of the voltage applied to the water-heater based on a set of linguistic rules. The development of the fuzzy rules and membership functions for the input and output variables are discussed in the next section. For further information on the theory of fuzzy logic, the reader is referred to any standard text on this subject, i.e. [13].

3. 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 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. The membership function for maximum water temperature allowed is not shown; it is similar to that for the customer comfort level with the sharp constraint set to the value of maximum water temperature allowed.

A very important task in fuzzy controller design is the development of fuzzy rules for the problem at hand. These rules depend largely on the experience and knowledge of the designer about the system at hand. In

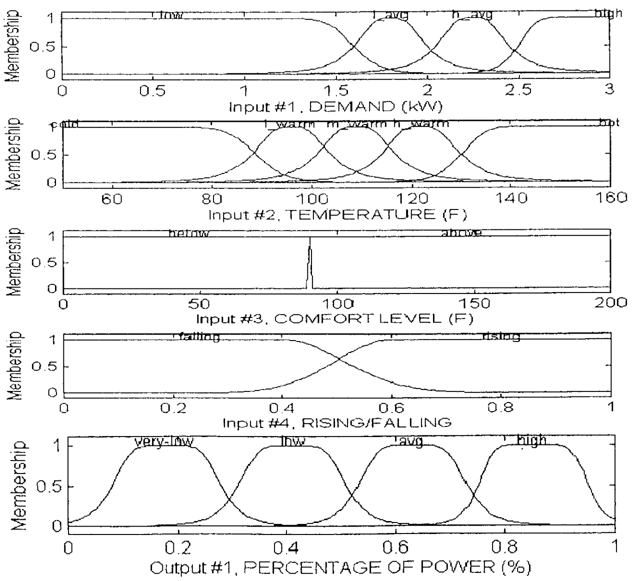

Fig. 3. Fuzzy membership functions.

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 hot water, should be met. Water temperature shall not fall below a minimum value set by the customer (in this case 95°F). 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. Moreover, power to the water-heater should be high if hot water temperature is near the set minimum value and decreasing.

4. 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, as reported in [11], may shift the peak(s) from one point in time to another. This situation can be avoided and distribution area water-heater demand profile can be better improved by dividing the water-heaters in a distribution area 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 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*, representing the low-demand regions of the total demand curve with slope near zero, 2) *Low-rising*, representing the low-demand regions with positive slope, and 3) *Low-falling*, representing 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) of water-heaters is expected to be a more level curve as compared to that when a single fuzzy controller is used to control all the water-heaters in a distribution area.

Fig. 4 shows the block diagram for the proposed multiple-block water-heater load shifting strategy, where the distribution area is divided into four blocks. Three of the blocks are controlled, each by a different fuzzy controller, as explained above, and one block is remained uncontrolled. The general block diagram for each fuzzy controller is similar to that given in Fig. 2. If desired, the upper temperature limit for hot water temperature can be set to a higher value than normal; it is set at 180°F in this study to make the most use of the

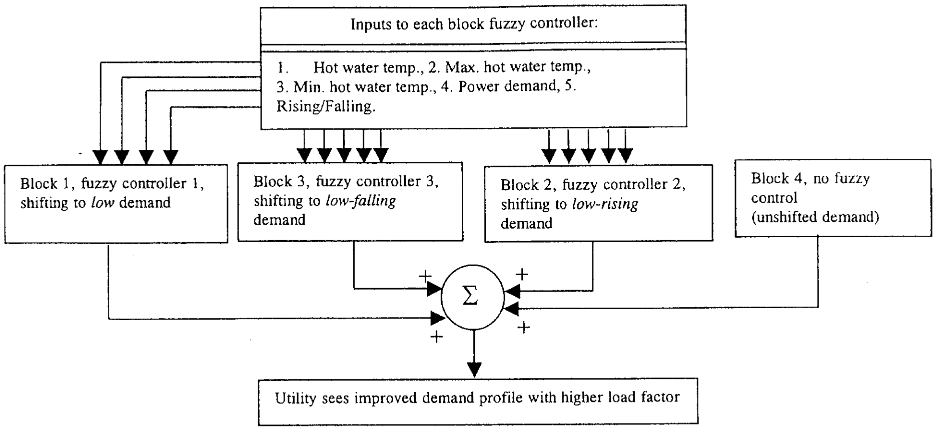

Fig. 4. Block diagram for multiple-block water-heater load shifting strategy.

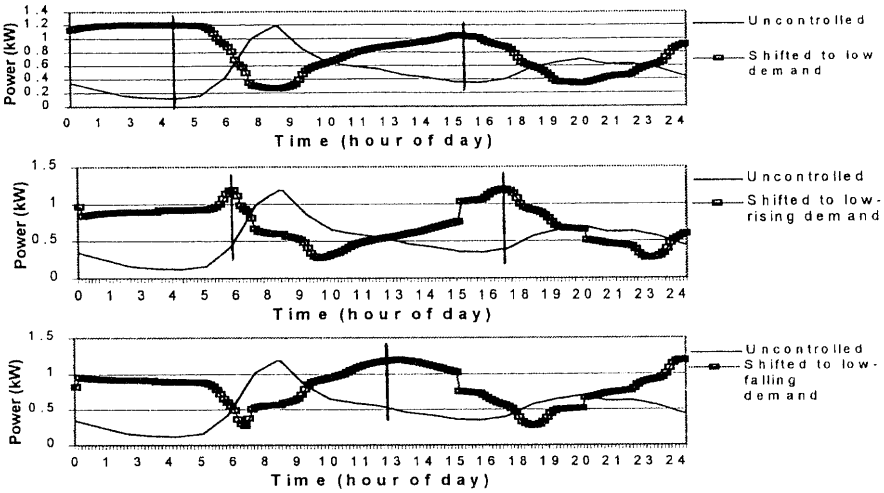

Fig. 5. Average water-heater power demand profile is shifted to three different time periods.

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 customers.

Membership functions for 4 input variables and the output variable for each fuzzy controller are the same as shown in Fig. 3. A fifth input to each fuzzy controller is a Boolean flag that indicates whether the power demand in the low-demand region of the distribution area power demand profile is either 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. In order to obtain correct information about the rising/falling status of the demand profile, proper filtering can be used to obtain a smooth profile (like that shown in Fig. 1).

5. Simulation results

A daily average residential water-heater power demand profile with water-heaters under thermostat control was generated (shown in Fig. 1) using an aggregate water-heater model [10]. This is called the water-heater power demand profile of an average house. Under thermostat control, each water-heater is either on consuming a fixed amount of powers (4.5 kW) or it is off. During normal operation, water temperature is kept very close to the thermostat set-point. However, under fuzzy control, power consumed by each water-heater at any given time is a percentage of the water-heater's rated power, which is determined by the fuzzy controller output signal [11]. In this reference, 22 rules were used to obtain satisfactory results.

In the proposed multiple-block DSM strategy, the water-heater demand profile of the average house under thermostat control (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 during which the demand is *low*, *low-rising*, and *low-falling*, as explained in Section 4. The average demand profile of the fourth block of water-heaters is kept uncontrolled (not shifted). For the controlled blocks, water is heated during the time periods where excess power is available. On the other hand, 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*. In this case, satisfactory control was achieved with only seven rules for each block's fuzzy controller. It is significantly fewer rules than the 22 rules needed for the single block fuzzy controller reported in [11]. The rules for the three regions (blocks) are listed in Appendix A.

Fig. 5 shows the shifted (controlled) and the conventional 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. The vertical lines show the shifted peak demands. Water temperature did not exceed 160°F or fall below 95°F for the average house water-heater for any of the blocks. Fig. 6 shows the hot water temperature profile for a typical fuzzy-controlled water-heater.

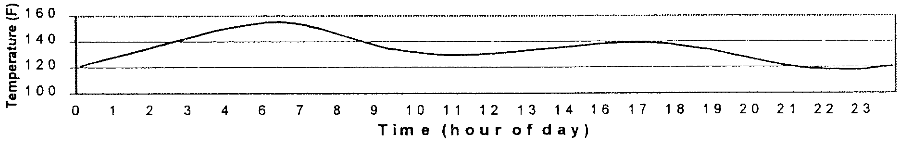

Fig. 6. Hot water temperature profile of a typical water-heater under fuzzy control.

Fig. 7 shows the average residential water-heater power demand profile under thermostat control and proposed the multiple-block fuzzy control strategy. For comparison purposes, the average water-heater power demand under thermostat control and when a single fuzzy controller is used (taken from [11]) are also shown in Fig. 8. It is clear from Fig. 7, that the peak of the water-heater demand profile under fuzzy control has been shifted to low-demand time periods and is about 33% lower than the peak of the thermostat-controlled demand profile. By comparing Figs. 7 and 8, it is also clear that the multiple-block fuzzy controlled strategy proposed in this paper is more effective and provides an improvement over the single fuzzy controller proposed in [11] in reducing the peak power demand and leveling the demand profile of a distribution area.

6. Conclusions

In this paper, a customer-interactive multiple-block fuzzy logic-based electric water-heater DSM strategy was presented for leveling the power demand profile of a distribution area. The 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 fuzzy DSM procedure can be effective in shifting the daily residential peak water-heater demand to off-peak hours. This will result in leveling distribution system power demand profile and therefore by improving utility load factor.

The proposed strategy can be attractive to the customers when effective financial incentives, such as real-time pricing of electricity, are provided to them by the utility to encourage their participation and co-operation with the program.

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Appendix A. Fuzzy Rules for Multiple Block shifting

A.1. Rules for shifting peak demand to low-demand period

1. If Demand is low, then Power is high.
2. If (Demand is l_avg) and (Rise_Fall is rising), then (Power is avg).
3. If (Demand is h_avg) and (Rise_Fall is rising), then (Power is low).
4. If (Demand is high), then (Power is very low).
5. If (Demand is h_avg) and (Rise_Fall is falling), then (Power is low).
6. If (Demand is l_avg) and (Rise_Fall is falling), then (Power is avg).
7. If (Comfort_Level is below), then (Power is high).

A.2. Rules for shifting the peak demand to low-rising period

1. If (Demand is low), then (Power is avg).
2. If (Demand is l_avg) and (Rise_Fall is rising), then (Power is high).

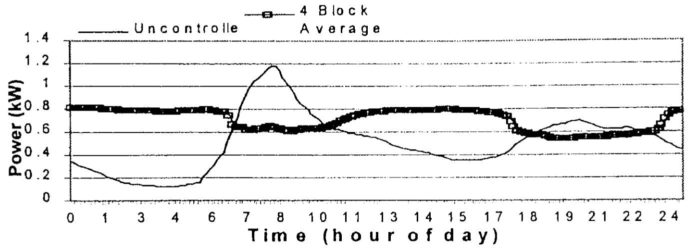

Fig. 7. Power demand profile for average of four blocks of water-heaters with three blocks being controlled.

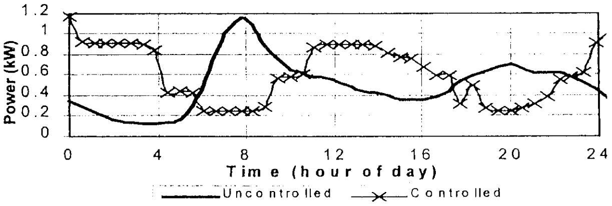

Fig. 8. Daily average water-heater power demand, uncontrolled and using a single fuzzy controller.

3. If (Demand is h_avg) and (Rise_Fall is rising), then (Power is avg).
4. If (Demand is high), then (Power is low).
5. If (Demand is h_avg) and (Rise_Fall is falling), then (Power is very low).
6. If (Demand is l_avg) and (Rise_Fall is falling), then (Power is low).
7. If (Comfort_Level is below), then (Power is high).

A.3. Rules for shifting the peak demand to low-falling period

1. If (Demand is low), then (Power is avg).
2. If (Demand is l_avg) and (Rise_Fall is rising), then (Power is low).
3. If (Demand is h_avg) and (Rise_Fall is rising), then (Power is very low).
4. If (Demand is high), then (Power is low).
5. If (Demand is h_avg) and (Rise_Fall is falling), then (Power is avg).
6. If (Demand is l_avg) and (Rise_Fall is falling), then (Power is high).
7. If (Comfort_Level is below), then (Power is high).

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