Design of Fuzzy Logic based Controller for Energy Efficient Operation in Building

Tingting He, Abhisek Ukil
School of Electrical & Electronic Engineering, Nanyang Technology University, Singapore
E-mail: the002@e.ntu.edu.sg, aukil@ntu.edu.sg

Abstract—Building energy management is a major R&D topic, as buildings account for a significant (~32%) portion of energy consumption worldwide. Design and implementation of controller for energy efficient operation in building is one of the methods to save the energy in the building. In this paper, a fuzzy logic based approach is used to design the energy management controller. Fuzzy logic has been widely used in the control engineering and many other fields of study. In the proposed approach, fuzzy logic is used to simulate the building load profile, and control the load of the appliance by flexibly choosing load scheduling. The controller would set a power threshold that cannot be exceeded, otherwise an on/off control of the home appliances would be invoked. In such a way, peak shaving of the power could be achieved. Using MATLAB-based graphical user interfaces, such fuzzy logic-based application could very well be implemented, reflecting on real-life scenarios.

Keywords—Building energy management, energy efficiency, fuzzy logic, load scheduling, low voltage distribution, peak shaving.

I. INTRODUCTION

With the concern of global warming and climate change, increasing focus is oriented towards energy efficiency. Energy efficiency is one of the approaches to contribute to the environment protection, a way of managing and restraining the energy demand. Moreover, it is researched that buildings consume approximately 32% of total energy consumption worldwide [1, 2]. With the constraint on natural resources in Singapore, increasing population and demand of electricity, energy is one of the key factors to affect the Singapore’s daily-life and economy in recent time and in the future.

This study is aimed at evaluating the possible energy reduction methods in the residential buildings during its peak hours. This research is focused on daily load profiles of 1 or 2 rooms, 3 rooms, 4 rooms and 5 rooms’ public housing [3,4].

Fuzzy logic is implemented to build up the profile and control the peak shaving. A ranking is decided to the home appliance and control the on/off of the appliances, as result of load reduction to the load during the peak hours [5–7]. Fuzzy logic is well suited for building energy management, as fuzzy rules and arithmetic could very well represent the appliance utilization pattern as per time of the day. The controller is developed using MATLAB fuzzy logic toolbox, and tested with residential data.

The remainder of the paper is organized as follows. In section II, background information on building energy is presented. Section III presents the load profiling of the residential buildings. Design of the fuzzy logic-based controller and the test results are presented in section IV, followed by conclusions in section V.

II. BACKGROUND INFORMATION

A. Classification of Singapore Buildings

The Singapore Residential Building is classified into Housing and Development Board (HDB) properties, condominiums, landed properties, and other apartments and other housing units which are less commonly found (e.g. housing units with mixed purposes, structure unique to local context). The detailed classification of the type of the dwellings is illustrated in Table I [1].

B. Singapore Residential Buildings Electricity Consumption

According to the report by the Energy Market Authority (EMA) in Singapore Energy Statistics 2015 [2], it is stated that there is about 3.3% rise in total energy consumption. In 2014, the total electrical energy consumption in Singapore was 46 TWh. There is an increase of 13 TWh of electricity consumption by the non-contestable consumers, as shown in Figure 1. More than half (52% or 6.9 TWh) of the loads was consumed by households. In 2014, household total electricity consumption increased by 2.5% to 6,936 GWh. About 59% (4,126 GWh) of total consumption was consumed by public housing units. Hence, it is meaningful and beneficial to research, study and find out a way to reduce the energy consumption in the residential buildings to improve their energy efficiency.

![Figure 1. Electricity Consumption by Contestability & Sector, 2014.](image-url)
III. RESIDENTIAL BUILDING LOAD PROFILE

No existing detailed data could be found for the daily household electricity consumption, as different houses may use different electricity appliances. Bottom-up approach is used to build up the total load profile based on the probability of daily appliance on/off [3].

A. One or Two rooms' Public Housing Load Profile

The residential appliances list, corresponding saturation level, nominal wattage, standby power, average daily starting frequency and time per cycle are shown in Table II [3] for 1 or 2 rooms flat. Its corresponding daily load profile is produced, as shown in Figure 2. The monthly electricity consumption is of 148.4 kWh. This data is used to model the load profile in fuzzy logic system for easier configuration.
B. Three rooms’ Public Housing Load Profile
Similarly, the average monthly electricity consumption for 3 rooms’ unit in Singapore is 278.2 kWh [3]. The daily load profile based on starting probability is shown in Figure 3 [3].

![Figure 3. Daily load profile of three rooms flat [3.]](image)

C. Five rooms’ Public Housing Load Profile
The average monthly electricity consumption for 5 rooms’ unit in Singapore is 447.8 kWh [3]. The daily load profile based on starting probability is shown in Figure 4 [3].

![Figure 4. Daily load profile of five rooms flat [3.]](image)

IV. FUZZY LOGIC APPROACH
This study mainly shows the plan of controlling the home appliances using fuzzy logic-based approach. Fuzzy logic has been successfully used in many energy efficiency applications [8–15]. This paper presents the procedure to design a controller for energy efficient operation, using the different time and load profiles. The process is based entirely on the principle of collecting all home appliances electricity power inputs from the sensors, subjecting them to fuzzy arithmetic and obtaining an integrated value of home total electricity power in each time. The controller would set a power threshold that cannot be exceeded, otherwise an on/off control of the home appliances would be invoked. In such a way, peak shaving of the power could be achieved, reducing unnecessary power to improve the energy efficiency of the home. Using graphical user interfaces, such fuzzy logic-based application could very well be implemented, reflecting on real-life scenarios.

A. Simulation of Public Housing Load Profile with Fuzzy Logic Application
Fuzzy Logic application is used to simulate the public housing daily load profile of one or two rooms, three rooms, and five rooms flats.

1) Definition of Daily Timeframes
The fuzzification process is described below, where first the daily timeframes are defined in 6 categories, as shown in Table III, and visualized in Figure 5.

<table>
<thead>
<tr>
<th>Input (Time) Description</th>
<th>Fuzzy Nomenclature</th>
<th>Time Range (24 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-night</td>
<td>MN</td>
<td>00:00 – 04:00</td>
</tr>
<tr>
<td>Early Morning</td>
<td>EM</td>
<td>04:00 – 06:00</td>
</tr>
<tr>
<td>Morning</td>
<td>M</td>
<td>06:00 – 09:00</td>
</tr>
<tr>
<td>Day</td>
<td>D</td>
<td>09:00 – 15:00</td>
</tr>
<tr>
<td>Afternoon</td>
<td>A</td>
<td>15:00 – 17:00</td>
</tr>
<tr>
<td>Night</td>
<td>N</td>
<td>19:00 – 23:00</td>
</tr>
</tbody>
</table>

![Figure 5. Daily timeframe description in fuzzification process.](image)

2) Definition of Daily Loads
Subsequently, the daily loads are defined, as shown in Table IV. A scale transformation is defined in terms of fuzzy linguistic variables, which maps the physical values into a scaled universe of discourse.
TABLE IV
FUZZIFICATION OF DAILY LOADS

<table>
<thead>
<tr>
<th>Input (Load) Description</th>
<th>Fuzzy Nomenclature</th>
<th>Range (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low Load</td>
<td>VL</td>
<td>0 – 300</td>
</tr>
<tr>
<td>Low Load</td>
<td>L</td>
<td>300 – 600</td>
</tr>
<tr>
<td>Medium Load</td>
<td>M</td>
<td>600 – 1500</td>
</tr>
<tr>
<td>High Load</td>
<td>H</td>
<td>1500 – 2000</td>
</tr>
<tr>
<td>Very High Load</td>
<td>VH</td>
<td>2000 – 3000</td>
</tr>
</tbody>
</table>

3) Definition of Output
The output is defined as percentage reduction in power output. The fuzzification of that is described in Table V.

TABLE V
FUZZIFICATION OF OUTPUT AS LOAD REDUCTION

<table>
<thead>
<tr>
<th>Output (%) Description</th>
<th>Fuzzy Nomenclature</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20%</td>
<td>20</td>
<td>0 – 0.2</td>
</tr>
<tr>
<td>40%</td>
<td>40</td>
<td>0.2 – 0.6</td>
</tr>
<tr>
<td>80%</td>
<td>80</td>
<td>0.6 – 0.8</td>
</tr>
<tr>
<td>100%</td>
<td>100</td>
<td>0.8 – 1.0</td>
</tr>
</tbody>
</table>

B. Design of Control Gramian with Fuzzy Logic Application
To automate this process, we use sensors to detect these parameters (i.e., time-specific input electricity power of the home appliances). Subsequently, the on/off control schemes of the appliances are determined from this data. The main objective here is to study the controllability gramian.

A model of the home energy load profile acts as input to the fuzzy controller. MATLAB fuzzy logic toolbox is used for designing the controller, with the fuzzy set rules.

The problem in this paper has been simplified by considering the input variables of time and degree (high/low) of electric power usage. Figure 6 shows the overall block diagram of the controller. The fuzzy controller takes the two inputs, processes the information and produces an output in terms of percentage of energy reduction value. The input variables are defined in the previous section. After defining the two input and one output variables, the following fuzzy rules are applied, which is shown in Figure 7. Figures 8-10 show the fuzzy rule surface views for 1 or 2 rooms, 3 rooms and 5 rooms flats.

C. Simulation using MATLAB/Simulink
Figure 11 shows the MATLAB/Simulink model for load reduction using the fuzzy logic. After getting the load reduction output from the fuzzy logic controller, load reduction is achieved as per Figure 11. Figures 12–14 show the energy savings in 1 or 2 rooms, 3 rooms and 5 rooms flats over the 24 hours. In Figures 12–14, the top plot shows the reduction of peak power, while the bottom plot shows the percentage of the peak reduction.
To achieve the total load reduction, individual loads should be considered. Therefore, an appliance specific load reduction priority list is set. This is shown in Table VI. Based on the priority list, the on/off scheduling would be done to achieve the load reduction.
V. CONCLUSION

Energy efficient operation in buildings has major focus worldwide. In this paper, fuzzy logic based approach is used to design the energy management controller. Bottom-up method is used to achieve the appliance level load profile. The electricity usage (power) and the time of the day are used as input variables to the fuzzy controller. The output of the controller is the reduction in load consumption of building and energy savings. Residential flats with different rooms are considered. Subsequently, a ranking is established for the different appliances so that the total load reduction can be achieved by activating an on/off control of the appliances.

ACKNOWLEDGMENT

This work was supported by the Energy Innovation Programme Office (EIPO) through the National Research Foundation and Singapore Economic Development Board.

REFERENCES