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Smart residential load reduction via fuzzy logic, wireless sensors, and smart grid incentives

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ABSTRACT

The incentives such as demand response (DR) programs, time-of-use (TOU) and real-time pricing (RTP) are applied by utilities to encourage customers to reduce their load during peak load hours. However, it is usually a hassle for residential customers to manually respond to prices that vary over time. In this paper, a fuzzy logic approach (FLA) utilizing wireless sensors and smart grid incentives for load reduction in residential HVAC systems is presented. Programmable communicating thermostats (PCTs) are used to control residential HVAC systems in order to manage and reduce energy use, while consumers accommodate their everyday schedules. Hence, the FLA is embedded into existing PCTs to augment more intelligence to them for load reduction, while maintaining thermal comfort. To emulate an actual thermostat, a PCT capable of handling both TOU and RTP is simulated in Matlab/GUI. It is utilized as a 'simulator engine' to evaluate the performance of FLA via applying several different scenarios. The results show that the FLA decreases/increases the initialized set points without jeopardizing thermal comfort by applying specific fuzzy rules through evaluating the information received from wireless sensors and smart grid incentives. Our approach results in better energy and cost saving in residential buildings versus existing PCT.

1. Introduction

Demand and supply should be balanced constantly in order to reduce power shortages, avoid interruptions in supply systems, and respond to energy management programs introduced by utilities. In grid-based energy supply systems, such as electricity, peak load demand management presents particular challenges for the generation and transmission of the energy demanded. In the past, insufficient capacity and its potential problems in the grid were often addressed at the supply-side. Nowadays, handling the peak load problems are being moved more towards the demand-side. From consumer point of view peak load demand management that results in load reduction means consumers adjust their schedules and preferences to the performance of the electricity system. For example, the residential consumers decrease or increase the set point (SP) temperatures of heating or cooling systems through their thermostats to reduce the electricity usage during specific periods. In addition, there are different actors with various interests when discussing peak load reduction. Each actor can regard peak load reduction from technical, economic, environmental, and even social aspects. For the residential customers, the economic, environmental, and social aspects have major significances [1].

Residential buildings have been one of the large sectors in terms of consuming energy [2]. They account for approximately 17% and 14% of total energy consumption in Canada and the U.S. respectively [2–4]. In addition, the residential electricity demand is predicted to increase by 24% within the following several decades [5]. Among all appliances in residential sector; HVAC systems are the main target for energy management and load reduction because they constitute a significant part of the annual total energy consumption in the world [1,2]. HVAC systems are also the main electrical load during the peak load periods. They can help to reduce regional electrical power demand and outages if they are controlled properly, more automated, and intelligence [1,6,7]. Moreover, electricity use for heating and cooling purposes is rapidly increasing due to population growth in hot/cold climates and greater demand for more comfort. The amount of energy to heat up or cool down homes comprised of approximately 64% and 54% of the total residential energy in Canada and the U.S. respectively [2–4]. Thus, the strategies for residential load reduction through control of residential HVAC systems have the potential to benefit both consumers and

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utilities from economic, technical and environmental aspects. Programmable Thermostats (PTs) are widely used to automatically control HVAC devices to conserve energy and provide indoor thermal comfort [6]. The main feature of PTs is programmability. By using PTs; users can set their preferences (e.g., SP temperatures) on a schedule basis. This operation is performed by turning the HVAC systems on or off based on the schedules and preferences adjusted by users. However, one of the major drawbacks of PTs is the households often fail or forget to use these devices the way that they are designed [1,6]. According to the survey reported in [6]; about 35–50% of the common U.S. households utilize the PTs as an on/off switch (conventional thermostat). Besides, according to energy information administration (EIA) in the U.S., during the heating season, 60% of households with PTs used them to reduce temperature at night but only 45% reduced the temperature during the day [6]. These are only because a PT by itself does not guarantee reduction in energy consumption. However, PTs totally depend on how they are programmed and controlled by the households. Hence, adding capabilities to make these devices more automated in order to shed the load demand, while providing user thermal comfort would overcome these issues.

Aforementioned issues, being limited to a single indoor temperature as well as lack of communication with new technologies such as smart meters are the major shortages of existing PTs. With the advancement in communication networks and wireless sensors, PTs were extended into programmable communicating thermostats (PCTs) [6]. PCT is a set of the controller and sensors which is equipped with LCD user interface, and wireless interface, for communications and network capability to sensors/actuators. On the other hand, a set of programs and incentives such as demand response (DR), time of use (TOU) rates, and real-time pricing (RTP) are applied by utilities and smart grids in order to encourage customers to reduce their energy usage during peak load demand (i.e., shedding or shifting consumption to off-peak hours or other times) [8–10]. Based on the TOU rates, the utility supplies the electricity at different rates during the day (e.g., On-Peak, Mid-Peak, and Off-Peak). In these regions such as Ontario, Canada, the consumers mostly know the electricity rates for different times of the day [11]. Hence, the households can potentially participate in DR events and TOU rates through presetting or scheduling their home appliances [8,10]. The primary motivations of applying smart grid incentives are for system reliability, handling emergency situations, preventing power outages, and environmental goals of smart grids [10,12,13].

The main feature of existing PCTs is capability of communicating with smart meters in order to read the electricity price signals, where the prices vary over time [14]. This feature potentially enables consumers to participate in DR events and TOU rates that will have a considerable impact on peak load reduction and greenhouse gas emissions [9,12,15]. PCTs also help households to save on high electricity prices [10]. The PCTs can potentially engage in DR programs based on TOU rates with user choice. In fact, the user can preset a price threshold, then manually enter different offset values associated with different TOU rates (On-peak, Mid-peak, off-peak) [14]. By doing so, the offset values are applied to the initialized SPs in order to decrease them in heating operation or increase the SPs in cooling operation thus resulting in load reduction. These offset values totally depend on the user's preferences and thermal feeling. Nevertheless, a significant thermal dissatisfaction has been reported during the participation in DR programs particularly in cold winters and hot summers [6,14]. This dissatisfaction requires users to constantly interact with their PCTs to change the offset values or opt DR out. The constant interactions irritate inconvenience to households and cause to behave with PCTs such as a single PT after a while [1,14]. In addition, it is usually a hassle and confusing for residential users to manually schedule their PCTs based on the prices that vary over time. Therefore, smart grid incentives require dynamic control capability (e.g., smart load reduction) to shed or shift the load(s) [16–18]. As a result, the need to augment more intelligence to PCTs to save energy and cost, while maintaining thermal comfort is apparent.

Fuzzy logic is a decision making model which is widely popular because of its capability in making reliable decision with minimal amount of information at hand. It has reasoning in the form of IF-THEN rules [19]. There are a large number of articles used artificial intelligence approaches such as fuzzy logic, genetic algorithm, neural networks, etc., in order to reduce the energy consumption in HVAC systems or optimize the operation of such devices [20–25]. A genetic tuning algorithm by considering an efficient multi-criteria method is proposed in [20]. They designed and tested several fuzzy logic controllers via experiment in order to verify the performance of their proposed controllers and tuning techniques. Their results show that the proposed technique has performed much better results than the classical On-Off controller. A survey on intelligent techniques that are used in HVAC systems is presented in [21]. They classified several intelligent approaches that were able to reduce and optimize the energy consumption in HVAC systems. In [26], an intelligent approach for auto-tuning of PID controllers is developed in order to control two damper gap rates in which the PID controller gains are computed by using fuzzy sets for the same HVAC system. In addition, an online fuzzy logic learning approach capable of adapting to the user's thermal preferences without any prior knowledge by aggregating several thermal parameters into one single thermal index is presented in [27]. However, our investigations demonstrate that the research on utilizing the technologies such as intelligent techniques, wireless sensors and existing smart grid incentives for energy management is in infancy [15,16,18,22,28]. Hence, monitoring and detecting environmental conditions such as occupant activity via wireless sensors and electricity prices via smart meters can enhance capabilities of existing in-home energy management systems.

The technologies such as integration of artificial intelligence approaches (i.e., fuzzy logic) using wireless sensors capabilities to make intelligent decisions in residential buildings can link DR, TOU, and/or RTP incentives with energy efficiency aspects [12,15,28–30]. In [31], a fuzzy logic rule-based approach using WSN is investigated and implemented in order to detect events such as fire and smoke in a field. Furthermore, residential energy management has become an important topic in research community. In [32], the design of an automatic controller to schedule home appliances in order to optimize the cost is investigated. Similarly, a particle optimization technique is also used to schedule demands in an automated way in [33]. However, in the most cases these approaches increase the peak-to-average ratio (PAR) during off-peak hours since these approaches are applied to shift the load to off-peak hours. Our approach relies on proactive demand shedding rather than demand shifting. In addition, a demand response controller based on RTP in order to curtail peak load demand and save electricity cost is presented in [34]. They have designed a price-based thermostat that reduces the load demand during high electricity rates. However, their approach is only price-based and does not take into account other important parameters such as occupancy and variations of outdoor temperature. In addition, they have not evaluated their approach with respect to user thermal comfort when the initialized set points are largely reduced during peak prices. They have not considered how their thermostat can curtail the peak load if the price mechanism is flat-rate. As a result, our approach is different than [34] since we attempt to reduce the residential demand based on different parameters such as occupancy, outdoor temperature, any kind of pricing, thermal comfort, and different schedules and preferences.