ARTICLE IN PRESS

Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

An adaptive fuzzy logic system for residential energy management in smart grid environments

Azim Keshtkar *, Siamak Arzanpour

Simon Fraser University, School of Mechatronic Systems Engineering, Surrey, BC, Canada

HIGHLIGHTS

- An autonomous system via supervised fuzzy learning under dynamic electricity prices.
- New adaptive model for adapting to pattern changes while maintaining existing rules.
- A fuzzy logic technique for residential load reduction in smart grids.
- Implementing a house energy simulator for energy management in smart grids.

ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form 7 November 2016
Accepted 8 November 2016
Available online xxxx

Keywords:
Adaptive fuzzy logic
Autonomous systems
Residential Energy management systems
Smart grids
Smart thermostats
Time-varying pricing
Wireless sensor networks

ABSTRACT

Heating, Ventilation and Air Conditioning (HVAC) systems represent a significant portion of total residential energy consumption in North America. Programmable thermostats are being used broadly for automatic control of residential HVAC systems while users initialize their everyday schedules and preferences. The main aim of smart grid initiatives such as time-varying prices is to encourage consumers to reduce their consumption during high electricity demand. However, it is usually a hassle to residential customers to manually re-programme their thermostats in response to dynamic electricity prices or environmental conditions that vary over time. In addition, the lack of energy management systems such as thermostats capable of learning autonomously and adapting to users' schedule and preference changes are major obstacles of existing thermostats in order to save energy and optimally benefit from smart grid initiatives. To address these problems, in this paper an adaptable autonomous energy management solution for residential HVAC systems is presented. Firstly, an autonomous thermostat utilizing a synergy of Supervised Fuzzy Logic Learning (SFLL), wireless sensors capabilities, and dynamic electricity pricing is developed. In the cases that the user may override the decision made by autonomous system, an Adaptive Fuzzy Logic Model (AFLM) is developed in order to detect, learn, and adapt to new user's preferences. Moreover, to emulate a flexible residential building, a 'house energy simulator' equipped with HVAC system, thermostat and smart meter is developed in Matlab-GUI. The results show that the developed autonomous thermostat can adjust the set point temperatures of the day without any interaction from its user while saving energy and cost without jeopardizing user's thermal comfort. In addition, the results demonstrate that if any change(s) occurs to user's schedules and preferences, the developed AFLM learns and adapts to new modifications while not ignoring energy conservation aspects.

1. Introduction

HVAC systems approximately constitute 64% and 57% of total residential energy consumption in Canada and the U.S. respectively [1,2]. Thus, residential HVAC systems are one of the main electrical loads for peak load management during peak demand periods. For example, these devices nearly comprised of 50% of the additional critical peak electricity consumption during hot summer days in California [3].

On the other hand, one of the main goals of smart grid incentives is to improve sight in order to lower network voltages as well as to enable customers' engagement in the operation of the power system, particularly through smart meters [4], smart energy management systems, and smart homes [5]. Moreover, the significance of distributed generation at medium and low voltages and other small renewables such as photovoltaic in consumer-side to locally

* Corresponding author.
E-mail addresses: akeshtka@sfu.ca (A. Keshtkar), arzanpour@sfu.ca (S. Arzanpour).

http://dx.doi.org/10.1016/j.apenergy.2016.11.028
0306-2619/

Nomenclature

AFLM	adaptive fuzzy logic model
AC	air conditioning
ASHRAE	American society of heating, refrigeration and air conditioning engineers
DR	demand response
FLC	fuzzy logic controller
HVAC	heating, ventilation and air conditioning
KB	knowledge base
MF	membership functions
PCT	programmable communicating thermostats
SFLL	supervised fuzzy logic learning
SP	set point
TOU	time-of-use
RTP	real-time pricing
WSN	wireless sensor networks
L_v	learning vector
l_n	elements of the learning vector, $n = 1, 2, \ldots, N$
w_n	associated weights of the elements of l_n
A_{z_m}	adapting vector for zone m
L_{Z_m}	learning vector for zone m
A_v	adapting vector
a_k	elements of adapting vector $k \leqslant n$
f_k	'overridflag' associated with each adapting vector
C_{ij}	weekday cluster, 'i' is day of week, '$j = m$' the number of occurrences within a particular day
$\hat{A}$	corresponding adapting vector
$A_{vc_{im}}$	a set of adapting vector under observation
$\hat{L}_v$	corresponding learning vector
$L_{vc_{im}}$	a set of learning vector under observation
Z_m	number of zones in the house, Z_1 (zone 1), Z_2 (zone 2)
$H_{k_{z_m}}cij$	heat set point value of the day i for set point number k
$C_{k_{z_m}}cij$	cool set point value of the day i for set point number k
$S_{k_{z_m}}cij$	start time of heat/cool set point
$E_{k_{z_m}}cij$	end time of heat/cool set point
$W_{H_{k_{z_m}}}cij.$	weights associated with set point $H_{k_{z_m}}cij$
$W_{C_{k_{z_m}}}cij$	weights associated with set point $C_{k_{z_m}}cij$
$W_{S_{k_{z_m}}}cij$	weights associated with start time $S_{k_{z_m}}cij$
$W_{E_{k_{z_m}}}cij$	weights associated with end time $E_{k_{z_m}}cij$
I_{Tz_m}	set point interval for time T in zone m
f_{kz_m}	'overrideflag' associated with set point number k in zone m

utilize them during peak demand periods in existing electricity supply has also been explained in [6]. Additionally, with advancements in communication networks and proliferation of deploying smart meters, management of peak load problems are being shifted towards the customer-side [7–9]. In [7], a holistic review has been conducted to summarize the initiatives and facilities that have capability to assist residential users to potentially save energy. The authors concluded that energy display devices by providing feedback to customers about their energy consumption can significantly help reduce energy consumption through shifting their electricity demands to off-peak hours. Authors in [8] attempted to propound the ways and services such as employing smart devices and smart meters that can encourage end-users such as residential customers in future to have an active role in future smart power grids. A novel air conditioning system has been developed by considering two demand response strategies namely demand side bedding and frequency controlled reserve in [9]. They used these strategies to bring up the role of both demand response programs and smart meters in saving energy and improving grid efficiency. In all communication networks within smart grids, considering the security issues is very important. A study on security issues in Microgids project platform has been conducted in [10], and the authors concluded these issues can be one of serious challenges in future smart power systems. As a result, smart meters as shared technology between users and power grids can enable residential customers to become an integral part of the electric power system. Moreover, time-varying electricity prices such as time-of-use (TOU) rates, real-time pricing, and combinations of these mechanisms provide various opportunities for residential users to reduce consumption and electricity bill by shifting the operation of their home appliances from on-peak rates to off-peak rates [11]. Nevertheless, load management strategy for residential HVAC systems can usually be performed by load shedding in response to different parameters such as time-varying prices [12], variations of ambient temperature [13], and in-home user activity (occupancy) [14]. Authors in [12] have accomplished a survey, where 15 houses as pilots have been used to compare the role of applying time-varying prices such as time-of-use and critical peak pricing in improving grid efficiency as well as saving energy. Additionally, the role of employing occupancy sensors in smart grids for saving energy through reducing the set point temperature of HVAC systems when the home in unoccupied was explained [14]. However, the authors in all these works only considered one parameter such electricity price or occupancy for controlling the energy consumption in the houses.

Fortunately, technology options such as employing home are networks [15] and installing energy display devices for monitoring HVAC energy consumption [16] as well as programmable thermostats [17] are also currently available to assist residential customers in order to manage and reduce their electricity consumption by shedding the demand of home appliances and HVAC systems during high electricity rates. Programmable communicating thermostats (PCTs) and price-responsive thermostats [18], and occupancy-responsive thermostats [19] are being used widely to automatically control residential HVAC systems while users initialize their everyday schedules (i.e., time intervals) and preferences (i.e., set point temperatures). PCTs and price-responsive thermostats potentially have capabilities for two-way communication such as using ZigBee communication protocols (IEEE 802.15.4) with utilities through deployed smart meters in order to participate in demand response (DR) programs with user choice [20]. The PCTs and price-responsive thermostats can receive price signals from smart grid and automatically decreases or increases the initialized set points to a level pre-defined by the user. Occupancy-responsive thermostats also keep monitoring occupancy and automatically change set points when a space or room is unoccupied. However, there exist major disadvantages to these thermostats. It has been reported repeatedly that users lose their thermal comfort particularly in cold winter days or hot summer days when they participate in DR programs during high electricity prices [19,21]. Authors in [19] found out that even existing smart home energy management devices cannot always save energy due to their dependent on user engagement. In this case, the users constantly re-adjust the pre-defined offsets in order to maintain their thermal comfort. However, it is often an inconvenience to residential users to continuously re-set the offset values in response to time-varying prices or occupancy [19]. Additionally, occupants often forget, neglect or even in many cases give up to

Please cite this article in press as: Keshtkar A, Arzanpour S. An adaptive fuzzy logic system for residential energy management in smart grid environments. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.11.028