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Adaptive residential demand-side management using rule-based techniques in smart grid environments

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ABSTRACT

Programmable Communicating Thermostats (PCTs) as price-responsive thermostats are being used broadly for automatic control of residential HVAC systems in North America. The main advantage of existing PCTs is their capability to receive pricing signals from smart meters and shed HVAC load during high demand. In these cases; PCT automatically reduces the initialized set points to the levels pre-adjusted by user. However, there still exist neglected potentials for demand-side management that resides in the control and interaction of PCTs. Hence, it requires making PCTs more intelligence to learn and adapt to user's preference changes which results in adaptive demand-side management. In this paper, an algorithm which is based on the integration of rule-based techniques and wireless sensors capabilities is presented. The proposed algorithm is embedded into exiting PCTs to improve their capabilities in learning and adapting to occupant's pattern changes. The simulation results demonstrate that PCTs equipped with our approach performs better than existing PCTs with respect to energy saving and adapting to occupant's pattern changes. To verify the feasibility of the algorithm; an embedded system using ZigBee wireless communication is built and applied to a conventional air conditioning (AC) system. The experimental results show the system precisely adapts to user's preference changes while saving energy and cost.

1. Introduction

Residential HVAC systems constitute a significant part of the world's energy consumption [1]. They almost account for 64% and around 43% of total residential energy consumption in Canada and U.S. respectively [2,3]. These devices are also the primary electrical loads during peak load periods that can lead to electrical peak load blackouts and regional power outages [1,4]. In addition, rising energy prices and transition from flat-rate to dynamic pricing such as Time-of-Use (TOU) rates will impact the households that their energy bills are significantly related to HVAC systems [5].

Programmable Thermostats (PTs) are still being used to automatically control HVAC systems in order to save energy and provide thermal comfort [6]. To use PTs as an energy management system in the house; the users accommodates the set point temperatures for different intervals of a day/week which indicating their schedules and comfort preferences. The PT uses a temperature measurement (sensor) in the level-crossing control logic with an adjusted set point. The thermostat requests heating or cooling if the measured temperature (indoor temperature) is greater or smaller than the initialized set point value based on the defined dead-band. However, several field studies show no significant savings in households using PTs compared to households using non-PTs [6,7]. In addition, another major obstacle of using PTs to conserve energy is that occupants often mistake to use these devices effectively [8]. For example, some users believe programming the PTs would be too much 'inconvenience' particularly when they have to repeatedly re-program their PTs in response to time-varying prices or outdoor temperature. Others forget or neglect to setback the set point values of PTs during night time or day time or reschedule their preferences [6,8]. These are the reasons that about 25% to 50% of the U.S. households with PTs use them like a non-programmable thermostat [6].

Furthermore, advancements in communication networks and wireless sensors have smoothed the path for researchers to utilize the capabilities of these technologies in their fields of interest [9]. The potential of using communication networks to residential sector was extended by National Grid Operators, Network Companies, and Electric Suppliers to build Advanced Metering

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Nomenclature

A	Area
ACS	Adaptive comfort standard
A_{flow}	Heated/cooled airflow
AMI	Advanced metering infrastructure
A_{sp}	Adapt set point vector
C	Specific heat capacity of the air
$\frac{dQ}{dt}$	Rate of heat/cool losses and gains
DR	Demand response
$E^j_{I_m}$	End time of set point $S^j_{I_m}$ for subinterval I_m and weekday j
GUI	Graphical user interface
HVAC	Heating, ventilation, and air conditioning
I_m	m different intervals for weekday
j	day of week, j = 1 Monday, j = 2 Tuesday, etc.
k	Thermal resistivity of materials
KB	Knowledge base
L	Wall thickness
M_{air}	Mass of air flow rate
O_n	Occurrence number n
P^j_m	Pattern vector for number of intervals (m) for weekday (j)
PCT	Programmable communicating thermostat
PMV	Predicted mean vote
PT	Programmable thermostat
q_h	Heated/cooled air supply into the house
R_{eq}	Equivalent thermal resistance of the house
RTP	Real-time pricing
$S^j_{I_m}$	Set point value corresponding to subinterval I_m for weekday j
$T^j_{I_m}$	Start time of set point $S^j_{I_m}$ for subinterval I_m and weekday j
T_{heat}	Heat temperature
T_{in}	Indoor temperature
TOU	Time-of-use
T_{out}	Outdoor temperature
$W^j_{E_{I_m}}$	Weight of start time E_{I_m} corresponding to interval I_m and weekday j
W^j_m	Weight vector for weekday j and interval m
$W^j_{S_{I_m}}$	Weight of set point value S_{I_m} corresponding to interval I_m and weekday j
$W^j_{T_{I_m}}$	Weight of start time T_{I_m} corresponding to interval I_m and weekday j
ΔT	Difference between indoor and outdoor temperature

Infrastructures (AMI) [10]. The purposes of deploying AMI technologies such as smart meters are to assist utilities to achieve their generation needs. These goals can be achieved through introducing and applying various programs such as different pricing mechanisms such as TOU and real-time pricing (RTP) and demand response (DR) programs [5,11,12]. These programs are often applied to encourage consumers to shift part of their electricity usage to off-peak hours or shed their consumption during on-peak periods [3,11]. Other objectives for employing AMI are to improve monitoring of energy distribution and transmission related energy losses and quickly identify power outages [10]. Thus, allowing customers (i.e., residential users) to conserve and save energy (on high electricity rates) as well as assist utilities to better manage peak load events. With advancements in communication networks, wireless sensors, and popularity of smart meters, nowadays, PTs have been developed into Programmable Communicating Thermostats (PCTs) [6,8]. Today's PCTs can communicate with other wireless appliances in the home and smart meters deployed by utilities to help both consumers on high electricity rates and utility in peak load demand periods [13]. Recent price-responsive thermostats, occupancy-responsive thermostats, and adaptable thermostats have demonstrated considerable annual residential HVAC energy savings around 10–20% [14]. However, the technologies used in this space vary widely. Some control techniques merely depends on remote management that the user adjust and change set points and schedules via web or smart-phone, while other devices keeps monitoring occupancy and automatically change set points when a space or room is unoccupied. There exist other technologies such as NEST thermostat that automatically adapt to user pattern changes in order to predict new user schedule changes and control HVAC operation. However, these different technologies can cause different savings implications which in many cases will jeopardize users' thermal comfort. In addition, the application in which any of these technologies is employed also impacts on the potential savings and operation of HVAC systems.

Seven reasons are summarized in [8] to demonstrate the importance and the role of residential thermostats such as PCTs and price-responsive thermostats in reducing peak load demand. For example, they concluded that by reducing the set point temperatures in winter during DR events or high electricity prices the thermostats can contribute to shave peak load demand. Thus, DR programs for residential devices such as HVAC systems can potentially benefit both consumers and utilities. However, consumers' knowledge regarding DR programs and even their impacts on electricity bill and energy management is fairly limited [14–16]. In addition, lack of knowledge among the residential customers regarding how to respond to time-varying electricity prices and DR programs [4,17] as well as lack of intelligence in residential energy management systems (i.e., PTs and PCTs) are two major drawbacks [14,18,19] for optimally utilizing the advantages of smart grid incentives. Missaoui et al. [20] discussed managing home appliances such as heating systems, washing machine and dishwasher from power grid aspects. Authors believe that GMBA that result in demand-side management is able to optimize a trade-off between user comfort and energy cost by taking into account several parameters such as occupant expectations, electricity prices and power restrictions. However, they have not considered the adaptability of their approach if the user overrides the decision made by GMBA.

Recently, several sophisticated appliance scheduling approaches for residential energy management have been proposed in [19,21–24]. They have suggested various techniques such as particle optimization, neural network-based prediction approach to schedule appliances in order to provide an optimum saving in energy and cost. These approaches are used for residential appliances to only operate autonomously, however they have not considered the alternative solutions if the users override the decisions made by autonomous system (i.e., lack of adapting to user schedule and preference changes).

Furthermore, the capabilities of wireless sensor nodes to observe, measure, and/or monitor different variables of interest (i.e., temperature, occupant activity, humidity) can help to enhance the limitations of the existing energy management devices [25–27]. Applications of ZigBee-based wireless sensors and wireless communications have been developed and investigated on various studies such as consumer electronics [28], buildings electrical safety [29], and for energy management and conservation in buildings [5,13,30,31]. These low-cost wireless sensor nodes could bring forward cost-effective mechanisms for monitoring, load control and energy management systems. The role of wireless technologies such as RFID and ZigBee wireless modems in residential buildings to achieve life cycle costs and energy conservation, improving