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Demand response for residential buildings based on dynamic price of electricity☆

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ABSTRACT

In the U.S., heating, ventilating and air conditioning (HVAC) systems are the largest consumers of electrical energy and a major contributor to peak demand. To reduce both peak load and energy cost, the set-point temperature of HVAC can be controlled depending on the electricity price. This paper presents a proposed controller that curtails peak load as well as saves electricity cost while maintaining reasonable thermal comfort. The controller changes set-point temperature when the retail price is higher than customers preset price. To evaluate the performance of the newly developed demand response controller, detailed energy models for two residential buildings are developed to analyze HVAC power consumption for different house sizes and floor plans. The house models are assumed to be located in Austin, Texas, USA and generated with OpenStudio and EnergyPlus. The design of internal load and occupation schedule are based on a residential energy consumption survey and experimental data by the Pecan Street Project, Austin, TX. In addition, historical data from Austin Energy for residential customers, 2012 is used to calibrate two house models. In addition, this paper uses the historical real-time wholesale price data for the Electricity Reliability Council of Texas (ERCOT) wholesale electricity market to model the two types of real-time tariffs that many utilities in the U.S. currently use to generate dynamic pricing for demand response programs. The simulation results show that our demand response controller could provide up to 10.8% of energy cost savings by using the proposed controller with dynamic pricing. While avoiding significant discomfort due to temperature change. Also, the results present potential for saving considering peak load by 24.7% and total electrical energy saving for HVAC in homes by 4.3% annually.

1. Introduction

Electrical energy consumption in residential buildings in the United States has generally been increasing from 2001 to 2011 except for a few years during the economic crisis. Moreover, the average retail price of electricity has gradually increased in nominal terms over the same period [1]. The energy and peak load growth necessitates new power plants and transmission lines. In hot climate zones, air conditioning (AC) loads are a major contributor to cause peak load on the power grid. For example, in Texas where the Electricity Reliability Of Texas (ERCOT) manages the power grid, the residential AC load was 6.1 GWh and 20% of grid electricity load on March 31, 2010. However, the residential AC load in ERCOT was tremendously increased to 35.3 GWh, 52% of total load, on August 3, 2010 [2] because of the hot weather. This heavy AC load during summer on the power grids in hot climates is the major contributor to peak load. Recently, there have been capital expansions that will tend to increase the retail price in real terms. Furthermore, due to heavy AC load, the cost for power generation is not only increased but also overall grid efficiency is reduced. This paper discusses a proposed demand response controller (DRC) and shows how it can be used for control of the AC system depending on the retail price of electricity. The objective of this study is to model the dynamic demand response controller that changes set-point temperature based on the dynamic price of electricity and occupant preferences. For dynamic price of electricity, two types of real-time tariffs are used by some utilities in the United States: Day Ahead Market Settlement Point Price (DAMSPP) and Real Time Market Settlement Point Price (RTMSPP). For houses with different sizes and floor plans, the study quantifies capacity to reduce peak loads as well as cost while maintaining the thermal comfort inside houses within an acceptable range.

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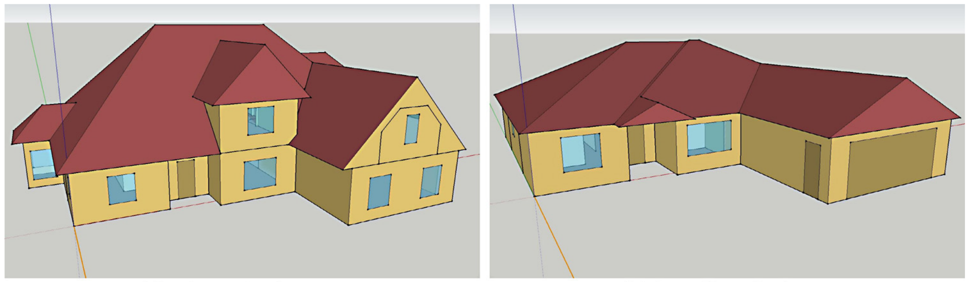

Fig. 1. 3D model of single family houses used in the study: large house (L) and medium size house (R).

In previous research related to the demand power control, large electricity loads such as commercial buildings, industries, retail and museums are analyzed to reduce high demand at peak time [3]. However, residential buildings are also a major contributor to peak loads. To address problems related to peak load caused by residential heating, ventilating and air conditioning (HVAC) systems, our previously developed DRC [4] is modeled in this paper in various residential buildings. Different from other dynamic response controllers analyzed in previous studies in [5–14], detailed house models are developed to analyze HVAC electricity consumption under consideration of various building geometries and physical properties that affect energy efficiency using EnergyPlus/OpenStudio energy simulation software [15–17]. The model developed for this study overcomes some shortcomings of previous DRC related research. For example, some of the previous studies related to DRC [5–9] did not have a HVAC model to control temperature, and therefore, could not analyze how much electricity is saved for cooling or heating during peak load period. Other studies related to demand response controllers [10–12] added simple HVAC models but the oversimplified Equivalent Thermal Parameter (ETP) model in their controller could not consider the impact of specific building features on the change of the set-point temperature. Building structures such as wall [18], attic [19], and windows [20,21] considerably influence the electricity consumption by HVAC. Our initial work on the development of DRC [4] provides the basic concept where a dynamic retail price is used in the demand response controller together with detailed house heat and mass model. In this paper, this work is extended to test the impact of saving and peak load reduction. The performance of DRC applied in two different size house models (shown in Fig. 1) also focuses on thermal comfort in different parts of the house.

We selected medium and large size of houses, common for U.S. residence (Fig. 1). The size and geometry of a house affect the total electricity consumption by HVAC, and these two houses with different size and floor plan are used to investigate how much the controller can reduce peak load for typical buildings in U.S. Detailed geometry and house thermo-physical properties are modeled in great detail since they affect an installed capacity of HVAC system as well as seasonal and daily dynamics of the energy consumption. This detailed modeling of building and HVAC systems provide the significant improvement over previously developed ETP models [10–12] that have no capabilities to analyze the complex thermal performance of multi-storey and multi-zone buildings. For example, previous studies could not account for the impact of large windows that increases the cooling load during summer and decreases heating load in winter [21]. Beside, better building physics models, the large house model used in this study is a two storey building with two HVAC systems and two thermostats controlling the upper and lower floors as two thermal zones.

Another advancement of our newly developed DRC is in innovative use of the retail price model. Previous work related to the retail price based control [22] used Critical Peak Price (CPP). However, this is partial real-time price since the price of electricity only changes during selected peaks and stays flat rate at other times. Similarly, the price data in [7] used the zonal market price of ERCOT for 2006. In 2010, ERCOT market changed from a zonal market to a nodal market where Real-Time Locational Marginal Prices are calculated every 5 min. In our study, the historical wholesale price of electricity in ERCOT's nodal market are used together with corresponding weather file for buildings' cooling and heating load calculation to synthesize a real-time tariff. Comparing to our controller that includes this real-time tariff in the decision about the set-point temperature change, the similar controller analyzed in the previous study [22] changes the electricity consumption by changing the set-point temperature without using the electricity price signal as an input.

When compared to our previous study [4], one of the advancement of the analysis in this paper is that it considers both day-ahead and real-time prices for customers because many utilities in the United States provide DR program to their customers with day ahead or real-time wholesale price based tariffs [23–25]. In the ERCOT wholesale market, the day-ahead price is calculated every hour one day before the electricity is delivered to the customers. In contrast to the day-ahead prices, real-time prices are calculated depending on current demand every 5 min. So, the customers receive a different price of electricity in the same period depending on whether the day-ahead or real-time prices are used.

Therefore, in the present study, two types of retail prices are used to analyze the advantages of price type and to show how much energy and cost can be saved with various types of pricing strategy. The price signals are input to two residential buildings' thermostat controllers in real-time using Building Controls Virtual Test Bed (BCVTB) [26]. Based on the algorithm described in the following section of this paper, the controller adjusts the thermostat set-point temperature. Since the temperature set-point change has consequences on thermal comfort, this study also evaluates the impact of control on indoor environments. To evaluate the thermal comfort in indoor environment when the controller changes the set-point temperature, in addition, the thermal comfort zone based on the latest ASHRAE Standard 55 [27] is used.

The following sections of the paper present the control strategy, specific about energy models for the analyzed buildings, retail price strategies along with simulation cases, and the results including peak load reduction. Also, cost savings and thermal comfort level for each type of house pricing strategy are illustrated. The summary and limitation of the current work along with direction for future work are provided in the final section of the paper.

2. Control strategies

The detailed control algorithm of the proposed DR controller for HVAC used in this paper is provided in our previous study [4], and in this section we provide the basic concept with detail related to the advancement of this controller. The control logic is as follow: