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Development of Matlab-TRNSYS co-simulator for applying predictive strategy planning models on residential house HVAC system

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ABSTRACT

Building energy simulators such as TRNSYS, EnergyPlus, and Esp-r offer an excellent opportunity for detailed design of house thermal model and its Heating, Ventilating, and Air Conditioning (HVAC) system and provide very accurate simulation results useful for performance analysis and optimization process. In contrast, these energy simulators do not include sub-models of advanced devices/strategies for control of HVAC system operation and suffer from poor control mechanism. In addition to lack of an advance controller, they inherently offer no mechanism for estimating the future state of their process models based on forecast weather dataset. Hence, no predictive controller can be designed and implemented within these simulators. This paper discusses the development of a Matlab-TRNSYS co-simulator in order to control/manage a TRNSYS program, which was previously developed and calibrated based on the characteristics of a real case study house, with an advanced predictive controller. This co-simulator investigates the effectiveness of different predictive strategy planning models, including Load Shifting (LSH), Smart Dual Fuel Switching System (SDFSS), and LSHSDFSS, as the integration of fuel switching and load shifting strategy planning models on 24 h ahead energy cost saving of the case study house HVAC system. Simulation results of different consecutive sample days indicate that SDFSS could bring significant energy cost saving. However, LSH and LSHSDFSS effectiveness is sensitive to the outdoor temperature.

1. Introduction

A high percentage of urban dwellings consists of residential houses (RHs). Hence, RHs can play significant roles in managing the network energy system. In order to investigate the effect of RHs on network energy system, different kinds of research have been previously conducted. For example, Mathew et al. [1] developed an internet-based distributed system utilizing distributed load shifting strategy to manage the community energy system. Liu and colleagues developed a constrained demand-side management system considering peak-to-average ratio and consumers' preferences in optimization routine for managing the energy systems of different residential houses [2]. Radhakrishnan and Selvan used load scheduling technique along with decentralization of power generation in various residential buildings to manage the network energy system [3]. In addition to their extensiveness, residential houses inherently have the potential for storing thermal energy, therefore, they present a great opportunity for managing/controlling electricity demand during peak hours utilizing various control techniques including advanced control system design [4] and (economic) model predictive control [5,6]. Furthermore, RHs energy systems can take advantage of various Strategy Planning Models (SPMs) to decrease the demand and particularly the energy cost at the user demand side. Naidu and Craig [7] present a chronological overview of the advanced SPMs implemented on heating, ventilating, and air conditioning (HVAC) and refrigeration systems. Weiss investigates an adaptive neuro energy management SPM in order to decrease the building energy cost [8]. Platt and colleagues used demand response experiments in two large office buildings [9]. Srinivas and Ning evaluated different demand response programs in order to analyze the benefits of applied SPMs [10].

Management and control of RHs energy systems have been extensively researched. For instance, García-Domingo designed a building integrated PV system to analyze the electrical energy balance of the house [11]. Keshtkar et al. [12] used smart wireless sensors in a residential house in order to reduce the electrical load. Onda et al. [13] utilized the storage system of the smart electric vehicle for shifting the house peak load to off-peak hours. Boehm [14] examined various approaches, including energy-conserving

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Nomenclature

ASH	Archetype sustainable houses
AHU	Air handling unit
ASHP	Air source heat pump
BCS	Best case scenario
CMC	Canadian meteorological center
COP	Coefficient of performance
DEC	Daily electricity cost
DFC	Daily fuel cost
DHW	Domestic hot water
DSO	Distribution system operators
HRDPS	High resolution deterministic prediction system
HVAC	Heating, ventilating, and air conditioning
LEED	Leadership in energy and environmental design
LSH	Load shifting
LSHSDFSS	Load shifting and smart dual fuel switching system
OEB	Ontario energy board
RH	Residential house
SDFSS	Smart dual fuel switching system
SPM	Strategy planning model
TOU	Time-of-use
TRCA	Toronto and region conservation authority

design and the use of photovoltaic arrays, to reduce the peak electrical demand in residences. Castillo-Cagigal et al. [15] examined the use of a semi-distributed demand-side management system to improve the house self-consumption capability. Fernandes et al. [16] developed a dynamic load management model for enhancing the participation of house in demand response events. Beizaee and colleagues [17] used zonal space heating controls to decrease the house demand. Naspolini et al. [18] investigated the benefits of solar water heating in house energy demand. Chassin et al. [19] examined the cost, comfort and energy impacts of a discrete-time controller in a residential house HVAC system. Li et al. [20] developed a dynamic zone modeling in order to reduce the HVAC system electricity cost. Nielsen and Drivsholm [21] developed a system in which ventilation was controlled by an intelligent demand controller. Among previous research, the ones that concentrate on residential HVAC load [17–21] are most useful and efficient since HVAC systems consume a significant portion of the total energy used in households. According to the Annual Energy Outlook published by the U.S. Energy Information Administration [4], HVAC systems consume more than 40% of the overall energy in residential houses resulting in higher operating costs and environmental pollution according to the Annual Energy Outlook published by the U.S. Energy Information Administration [4]. Over the past decade, numerous strategy planning and energy conservation methods/approaches have been developed to address the planning issues related to managing RHs and their HVAC systems energy demand and associated cost. For example, Ma and colleagues [5] showed that HVAC system energy cost can be reduced using thermal storage in building mass. Candanedo and Athienitis [6] examined the effect of floor heating mass on reducing the energy cost. In this study, the impacts of passive solar gains on managing the HVAC system energy demand, were considered. Temperature reset during unoccupied hours [7,8], night setback, precooling during off-peak period and set-point change during peak hours [9,10], optimum start and stop times [22], ventilation control [23,24] and economizer cycle control [25] are some of the SPMs implemented on HVAC system in order to decrease its energy demand and associated cost.

Many of the previous studies utilized house energy simulators such as TRNSYS [26], EnergyPlus [27,28], Mathcad [29], and Esp-r [30,31]. These energy simulators offer an excellent opportunity for detailed design and modeling of the house and its HVAC system and provide very accurate results useful for performance analysis and optimization process. In contrast, these simulators do not include sub-models of advanced devices/strategies for controlling the HVAC system operation and suffer from poor control mechanism. As a result, only simple conventional (on/off) controllers were employed in order to control and manage the house and its HVAC system performance. Due to the large thermal inertia of the conditioned zone and dynamic disturbances, the on/off controller cannot accurately regulate the zone temperature resulting in thermal discomfort for the occupants and higher energy costs [4,32]. In addition to the lack of advanced controllers, these energy simulators use operational/historical weather dataset (provided in a library file) for simulating the house's energy system. Hence, they inherently offer no mechanism for estimating the future state of their process models based on the forecast weather dataset. In the advanced predictive controller, a model of the system (building and its HVAC system) and the forecast weather conditions are used to determine the best set of control operations [4,32]. Hence, no predictive controller can be designed and run within such building energy simulators.

Therefore, in order to control the process models of such software with advanced and/or predictive controllers, a software/tool with advanced process control mechanism (i.e. Matlab) should be integrated/linked into these building energy simulators. This study discusses the development of a Matlab-TRNSYS co-simulator in order to control/manage the TRNSYS program with an advanced predictive controller. To design an advanced controller, three novel predictive strategy planning models (SPMs) including Smart Dual Fuel Switching System (SDFSS), Load Shifting (LSH) and LSHSDFSS as the combination of SDFSS and LSH-SPM models are developed in this study using Matlab program. To implement these predictive SPMs on the TRNSYS model, Matlab and TRNSYS programs are linked together to found a Matlab-TRNSYS co-simulator. The TRNSYS (TRNSYS 16) model utilized in this study has been previously developed and calibrated based on the characteristics/specifications of a real case study house (Archetype House A) [41]. In this study, the advantage of the developed co-simulator is examined by investigating the effectiveness of each SPM on HVAC system energy cost saving for the next 24 h horizon time. In this method of control, the future state of the system is predicted based on the forecast weather dataset, the system model, and control vector signals (generated as the model output) which drive the system towards the desired state. This co-simulator, which acts as a smart grid-friendly controller, also has the potential to be utilized as a test bed for implementing various SPMs previously developed for reducing the energy cost of HVAC systems.

This article consists of four sections. In Section 2, different formats of forecast weather dataset are described. The process model and the different strategy planning models are then described in detail as well. The simulation result as well as the effect of each SPM on the demand and energy cost of the case study house HVAC system are discussed in Section 3. The study is concluded in Section 4.

2. Model description

2.1. Historical and forecast weather information

Weather conditions play a significant role in house energy system simulation. As a result, getting access to accurate weather