Control Engineering Practice 72 (2018) 192–205

Contents lists available at ScienceDirect

Control Engineering Practice

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

A simulation and control model for building energy management

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A R T I C L E I N F O

Keywords:
Building energy management
Appliance control
Simulation
Petri Net
Matlab/Simulink

A B S T R A C T

This paper deals with the energy consumption management problem in buildings by modeling and controlling the main electric appliances. Renewable energies are taken into account by considering the production schedules of both wind and solar sources. Each appliance is described by modular mathematical models by means of the Matlab/Simulink software. A simulator is designed that models the load energy consumptions and helps to recognize how they contribute to peak demand. Moreover, a controller to manage the load usage is designed in a Petri Net framework. In the proposed control strategy, the comfort conditions are respected for each appliances on the basis of the user preferences. Finally, a real case study validates and tests the effectiveness of the simulator applied to the considered appliances.

1. Introduction

One of the main problems to be faced in the near future is the increase of the power demand. Indeed, in the next decade, power demand is estimated to rise by 19% and the existing infrastructures can increase their productivity by only 6% (Gudi, Wang, Devabhaktuni, & Depuru, 2010). In the last years, the building energy consumption amounts to around 30% of all energy consumed in advanced countries. In this context, it is important to encourage the building and business owners to adopt new technologies in order to reduce the demand for the electric grid (Deshmukh & Deshmukh, 2008). The literature is poor in accurate real-time simulation and control tools for the Building Energy Management (BEM), even if the building energy consumption represents much of the total energy consumed in advanced countries.

This paper proposes a detailed model devoted to simulate the building appliance energy consumptions and control the loads usage by a strategy that takes into account both the total building energy consumptions and the respect of the comfort conditions. The object of the paper is twofold: (i) providing a simulation framework in order to promote the utilization of new Information and Communication Technology (ICT) tools to reduce the demand on the electric grid; (ii) proposing a control logic to force the building appliances to follow a demand reduction strategy. In particular, the controller is modeled as a Discrete Event System in a Petri Net (PN) framework. Moreover, the control strategy is applied in a simulation environment describing the dynamics of the following loads: Heating Ventilation and Air Conditioning (HVAC) system, water heater, dishwasher, washing machine, refrigerator, freezer, oven, iron, TV, PC, dimmable lamps and renewable sources such as photovoltaic and eolic. In particular, the demand reduction strategy is implemented by a Building Energy Management System (BEMS) and aims at monitoring the real-time building energy consumptions in order to:

- avoid the overcoming of power provided by the electric grid;
- respect the user comfort by an intelligent power reduction based on a priority list of the electric loads.

An example of the use of the priority criteria in order to manage the domestic electric loads can be found in Pipattanasomporn, Kuzlu, and Rahman (2012). Moreover, a discrete-event formalism modeling the controlled system dynamics is presented for testing alternative priority lists and capturing emerging criticalities. To this aim, the proposed PN model is both a mathematical tool for process simulation and a graphical tool (Peterson, 1981) for allowing a modular design of discrete event system controller. Furthermore, the PN can be automatically converted into commonly used language for Programmable Logical Controllers (PLCs) (Bender et al., 2008).

This paper is organized as follows. Section 2 reviews the literature on BEM, while Section 3 presents the simulation framework and its components. Section 4 describes the loads model in detail while Section 5 shows the controller model. Moreover, Section 6 introduces a real case study and analyzes the simulation and validation results. Finally, in Section 7 the conclusions are drawn.

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https://doi.org/10.1016/j.conengprac.2017.11.010
Received 17 March 2017; Received in revised form 28 November 2017; Accepted 30 November 2017
0967-0661/

2. Literature review

Recent researches focus on energy management problems and the proposed technological solutions can be divided in two main categories (Chaouch & Slama, 2014; Fanti, Mangini, Roccotelli, & Ukovich, 2015)

- predictive energy management;
- real time control algorithms.

The predictive energy management research proposes model predictive control methods which incorporate both forecasts and updated information in order to obtain an optimal appliance scheduling. Such models mainly aims at minimizing the building energy costs (Chen, Wang, Heo, & Kishore, 2013; Dong, Malikopoulos, Djouadi, & Kuruganti, 2016; Li et al., 2016; Prívara, Cigler, Váňa, Oldewurtel, & Žáčeková, 2013; Wu, Hu, Yin, & Moura, 2016).

Chen et al. (2013) present an appliance scheduling scheme for residential BEM controllers in order to minimize the energy costs. Finite-horizon scheduling optimization problems are formulated to exploit operational flexibilities of thermal and non-thermal appliances using a model predictive control method which incorporates both forecasts and newly updated information.

In Prívara et al. (2013) the authors address the problem of finding the optimal control action for heating, cooling, ventilation, blind positioning, electrical lighting, humidity. The proposed appliance scheduling is determined in such a way that the temperature, CO_2 and luminance levels in building zones stay within the desired comfort ranges and the physical and economic constraints are satisfied.

Moreover, papers (Dong et al., 2016; Li et al., 2016; Wu et al., 2016) solve an optimal stochastic control problem for the home energy management system. Indeed, Li et al. (2016) develop an integrative demand response strategy based on two stage stochastic programming model that considers the energy usage of critical appliances to be essentially stochastic. The optimization objective is to minimize a customer electricity cost. In addition, Dong et al. (2016) models the building energy system as pure stochastic differential equation models, and then the authors follow the completing square technique to solve the stochastic home energy management problem. Finally, in Wu et al. (2016) a stochastic dynamic programming framework for the optimal energy management of a smart home with plug-in electric vehicle energy storage is proposed.

The second research category develops optimum operation scheduling models of domestic electric appliances using integer linear programming and simulation frameworks. The goal is to reduce peak power, energy costs taking into account the customer comfort range (Abaalkhail, Orozco, & Saddik, 2012; Franceschelli, Gasparri, & Pisano, 2016; Hansen, Chong, Suryanarayanan, Maciejewski, & Siegel, 2016; Lai, Rodrigues, Huang, Wang, & Lai, 2012; Li, Zhang, Roget, & O'Neill, 2014; Molitor, Togawa, Bolte, & Monti, 2012; Pilloni, Floris, Meloni, & Atzori, 2016; Wang & Paranjape, 2014; Yu & Dexter, 2010; Zhang, Li, Sun, & O'Neill, 2016).

In particular, papers (Abaalkhail et al., 2012; Franceschelli et al., 2016; Li et al., 2014; Zhang et al., 2016) propose intelligent energy controller algorithms that efficiently manage energy consumption for both heating and cooling appliances. In Abaalkhail et al. (2012) a distributed intelligent energy algorithm that minimizes energy use in the heating and cooling system within the home by taking into consideration occupant preferences is proposed. Li et al. (2014) presents a computational experiment approach to develop and investigate demand response strategies for the HVAC system of a typical residential house. The authors use four different demand response algorithms: optimization, particle swarm optimization, heuristic method and an integrative computing platform that combines a home energy simulator and MATLAB together. Moreover, Franceschelli et al. (2016) considers a distributed and cooperative approach for coordinating the power demand of electric thermal systems while Zhang et al. (2016) focuses on developing an interdisciplinary mechanism that combines machine learning, optimization, and data structure design to generate optimal demand response policies for HVAC systems.

Since the energy system of the future is expected to be composed of a large variety of ICT tools, recent works investigate the problem of controlling each typology of electric appliances. In particular, the energy systems may lately make use of new controllers and communication infrastructure and benefit from cyber-physical system advantages (Palensky, Widl, & Elsheikh, 2014). Moreover, the use of low-power narrowband power line communication can support home energy management systems with respect to the limits of wireless communication. Indeed, in a home framework it is difficult to communicate with all electric appliances for the presence of walls or obstacles. On the other hand, the use of narrowband power line communication greatly improves the packet success rate to the electric appliances (Ikpehai & Adebisi, 2016).

Wang and Paranjape (2014) propose an agent-base model to evaluate the BEMS in residential demand response implementation. In particular, the BEMS intelligently controls household loads with association of smart meters. The proposed model can be considered as a test-bed to evaluate various demand response strategies and technologies.

Moreover, Hansen et al. (2016) presents a home energy management system that schedules the energy usage in a smart home in response to utility pricing signals. Yu and Dexter (2010) propose a model-free method using reinforcement learning scheme to tune a supervisory controller for a low-energy building system online.

In addition, Lai et al. (2012) present a smart appliance management system to recognize electric appliances in home networks, which uses sensing devices that measure current to calculate the power consumption of the appliances. The paper is focused on the architecture to be designed for monitoring the electric appliances.

In this field Fanti, Mangini, and Roccotelli (2014) propose a PN model to describe the behavior of a controller that manages the home appliance in order to reduce consumptions.

The authors of Molitor et al. (2012) investigate the possibility to support the development of home energy systems and residential micro grid concepts by simulations including detailed load models in order to improve the efficiency of the applied energy management strategy or control strategy.

In this context, Gudi et al. (2010) propose an optimized operation of household appliances in a Demand-Side Management (DSM) based simulation tool. In particular, the main purpose of the authors is to illustrate customer-driven DSM operation, and evaluate an estimate for home electricity consumption while minimizing the customer's cost. A binary Particle Swarm Optimization is used for optimizing the DSM operation. The consumption of appliances is deducted by data-sheets that report the energy consumption in steady state.

Moreover, Chaouch and Slama (2014) presents a novel algorithm based on adaptive scheduling to reduce energy during peaks hours without affecting the comfort of occupants in a smart home. The proposed approach is described and applied to a realistic example simulated in Matlab/Simulink framework.

On the other hand, Pilloni et al. (2016) analyze the issue of introducing adjustments in the appliances' scheduling during the user working period for energy cost savings. The authors propose a Quality of Experience aware smart home energy management system, which relies on the knowledge of the annoyance suffered by the users when the operations of appliances are changed with respect to their ideal preferences.

2.1. Paper contribution

In the related literature, simulation and control studies have paid less attention to the problem of appliances' scheduling operations. However, some works (Chaouch & Slama, 2014; Molitor et al., 2012) highlight the possibility of developing BEMSs by simulations. Moreover, the authors