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Integrated automation for optimal demand management in commercial buildings considering occupant comfort

Fakeha Sehar*, Manisa Pipattanasomporn, Saifur Rahman

Virginia Tech, Advanced Research Institute, Arlington, VA, 22203, USA

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ABSTRACT

Implementing demand response (DR) in commercial buildings can play a major role in reducing building's peak load. This improves the efficiency of electricity grids and mitigates expensive peak demand/energy charges for buildings. Due to the lack of Energy Management Systems, small and medium-sized commercial buildings have not historically played much role as a DR resource. This paper presents an integrated control of major loads in commercial buildings, i.e., cooling, lighting and plug loads that can maintain occupant environmental preferences. Each zone's space temperature set points are optimally adjusted to maintain thermal comfort. Lighting levels, with and without daylight availability, are tightly controlled to maintain desired illuminance levels. Unlike other studies, this research contributes to improvement in functionalities of EnergyPlus by incorporating a 1-min resolution data set at the individual plug load level. The research evaluates total building performance including interdependencies between lighting, plug load, HVAC and control systems interacting in a realistic manner, both among themselves and with building occupants. In this paper, a method to determine the DR potential of a building, i.e., the amount of electrical demand (kW) by load type that can be shifted or shed, is discussed.

1. Introduction

Implementing Demand Response (DR) programs in buildings provides opportunities for peak demand reduction (FERC, 2011; Kreuder & Spataru, 2015; Wang, Biviji, & Wang, 2011) and in doing so help reduce energy costs (Smith & Brown, 2015) and increase renewable energy share (Gils, 2014). DR provides control of end users' electrical demand in response to grid signals (Yan, Xue, Wang, & Cui, 2015). DR changes the time pattern and magnitude of utility's load and results in increasing the efficiency and use of system assets (Gelazanskas & Gamage, 2014). The use of Energy Management System (EMS) is not widespread in small and medium-sized commercial buildings (<9290 m^2) (Goldstein & Bloom, 2014; Katipamula et al., 2012). These buildings represent 94% of all commercial buildings, and consume 44% of the total energy of the commercial buildings in the U.S. according to the Commercial Building Energy Consumption Survey (CBECS) 2012 (EIA, 2012). Due to the lack of controls significant amount of energy consumed in these buildings is wasted (Katipamula et al., 2012).

Among different types of commercial buildings, office buildings consume more than 17% of the total energy used by the commercial buildings sector in U.S. (EIA, 2010). Major end-use loads in office buildings are lighting, cooling and office equipment, which account for about 39%, 14% and 15% of electricity consumption respectively (EIA, 2008). There are studies that discuss possible DR strategies for controlling Heating, Ventilation and Air-Conditioning (HVAC), lighting and plug loads. These studies are summarized below:

1.1. HVAC-based DR strategies

Usually commercial buildings are overcooled (Derrible & Reeder, 2015). (Page, Kiliccote, Dudley, & Piette, 2011) demonstrated and showed limited DR savings due to non-optimized DR strategies and lack of customer awareness towards DR. They concluded that there is a need to improve DR performance for small and medium-sized commercial buildings and measurement of load reductions from end-uses. Different HVAC-based DR strategies include global temperature adjustment of zones and systemic adjustments to the air distribution and cooling systems (Motegi,

Abbreviations: ASHRAE, American Society of Heating Refrigerating and Air-Conditioning Engineers; CBECS, Commercial Building Energy Consumption Survey; DF, Daylight Factor; DOE, Department of Energy; DR, Demand Response; DX, Direct Expansion; EMS, Energy Management System; Erl, EnergyPlus Runtime Language; HVAC, Heating Ventilation and Air-Conditioning; IESNA, Illuminating Engineering Society of North America; PMV, Predicted Mean Vote; PNNL, Pacific Northwest National Laboratory; VAV, Variable Air Volume.

* Corresponding author.
E-mail addresses: sehaf0@vt.edu, fakeha.sehar@gmail.com (F. Sehar).

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Piette, Watson, Kiliccote, & Xu, 2007). (Watson, Kiliccote, Motegi, & Piette, 2006) and (Motegi et al., 2007) field-tested HVAC-based DR strategies, and indicated global temperature adjustment of zones best achieves DR goal. (Tzivanidis, Antonopoulos, & Gioti, 2011) correlated cooling energy usage with thermostat operation to better understand relationship between energy consumption and thermal comfort. (Yanga, Yana, & Lam, 2014) provided a summary of some case studies analyzing energy consumption with changes in summer set point temperatures. (Plat, Ward, & Wall, 2011) showed that applying global set point changes during peak hours results in poor distribution of HVAC capacity across zones and an uneven distribution of occupant satisfaction across the building. (Al-Mulla & ElSherbini, 2014) reported demand savings associated with closure of air-conditioning units or rise in cooling set points for different types of buildings. (Sehar, Pipattanasomporn, & Rahman, 2016) showed that although global temperature adjustment was able to achieve more peak load savings but is unable to maintain thermal comfort in all zones across a building.

1.2. Lighting DR strategies

Control of electric lighting adapting to changes in occupancy and daylight while maintaining illumination comfort can reduce building energy consumption. (Dubois & Blomsterberg, 2011; Galasiu, Atif, & MacDonald, 2004; Newsham, Aries, Mancini, & Faye, 2008; Park, Ryu, Choi, & Kim, 2014; Shen, Hu, & Patel, 2014) discussed different types of lighting control strategies for peak load reduction including harvesting daylight, continuous dimming and on/off strategies implemented in commercial buildings. (Al-Mulla et al., 2013) showed peak demand savings of 0.23 MW achieved in a group of eight buildings with de-lamping for a typical summer day. (Shen et al., 2014) demonstrated poor light performance for lighting control integrated with occupancy and HVAC in cooling dominated spaces. (Galasiu & Veitch, 2007) provided an overview of occupant behavior from studies examining occupant preferred light levels in office buildings with natural daylight available and light controls. (Boyce et al., 2006; Moore, Carter, & Slater, 2002; Veitch & Newsham, 2002) indicated that occupants prefer illuminance levels lower than recommended values. (Ashley & Reynolds, 1994; Gentile, Laike, & Dubois, 2014; Love, 1998; Moore, Carter, & Slater, 2003) indicated occupants electric lighting use is seldom affected by daylight availability, higher levels of electric light use have been observed with higher external illuminance (Begemann, Beld, & Tenner, 1997; Gentile et al., 2014). In order to get benefits from daylight control, automatic controls either providing automatic lights switching or photoelectric dimming are needed to avoid the risk of more energy usage.

1.3. Plug loads DR strategies

Plug loads are defined as electricity-consuming loads which are different than building end-use loads including HVAC and lighting. Office buildings are usually unoccupied 66% to 75% of the hours in a year and occupants are usually seated at their desk for about 10% of the year (Lobato, Sheppy, Brackney, Pless, & Torcellini, 2012; Metzger, Cutler, & Sheppy, 2012). A plug load control strategy devised to match plug load use with occupancy is a huge untapped potential for energy savings (Lobato et al., 2012). (Kamilaris, Kalluri, Kondepudi, & Kwok Wai, 2014b) discussed energy metering, taxonomy and modes of operations of office equipment. (Kaneda, Jacobson, & Rumsey, 2010; Kawamoto, Shimoda, & Mizuno, 2004; Kwong, Goh, Adam, & Raghavan, 2014; MACEBUR, 1998; Mungwititkul & Mohanty, 1997; Nordman, Meier, & Piette, 2000; Poll & Teubert, 2012; Webber et al., 2006) indicated that office equipment is usually left on during unoccupied periods. (Gandhi & Brager, 2016) indicated that behavior based control can achieve cost effective energy savings. (Acker, Duarte, & Wymelenberg, 2012; Kaneda et al., 2010; Metzger et al., 2012) proposed occupancy and load sensing plug strips to automatically shut down electric equipment and save energy. (Arnold, Sankur, & Auslander, 2013; Weng, Balaji, Dutta, Gupta, & Agarwal, 2011) presented a control algorithm to manage few local office plug loads to meet the load shed target while minimizing occupant's inconvenience. When modeling plug loads in buildings, they are assumed to be static devices with pre-determined parameters, leading to simulation results exhibiting low fidelity (Kamilaris et al., 2014b).

Based on the literature, it can be concluded that there is a lack of optimal DR management that can control all major loads (HVAC, lighting and plug loads) and quantify DR potential in small and medium-sized commercial buildings. Previous studies have rarely reported comfort performance; it is important that buildings provide comfortable indoor environment necessary for productivity of occupants (Aduda, Labeodan, Zeiler, Boxem, & Zhao, 2016). For HVAC control, literature review shows that mostly buildings apply global temperature adjustment to achieve HVAC energy savings. This scheme may not be able to meet occupant comfort satisfaction, as all thermal zones do not behave the same. For lighting control, typically daylight control with automatic light switching or loosely coupled photoelectric dimming is implemented in buildings. For plug load control, there are a limited number of studies discussing control of plug loads at building level. Building's plug loads are usually modeled by lumping all plug loads together, and the total plug load power consumption is determined by using a constant plug load density (i.e. W/m^2) together with the plug load schedule. There is a need to explore load duration curves of key plug loads in order to better map how usage patterns affect consumed power (Kamilaris, Kalluri, Kondepudi, & Kwok Wai, 2014a) and help in automating DR management in peak load scenarios (Weng et al., 2011). There is also a knowledge gap with regard to impacts of controlling commercial building's plug loads on the building load profiles (Acker et al., 2012).

To address the above knowledge gaps, the authors propose integrated automation for optimal control of major loads in commercial buildings including cooling, lighting and plug loads while occupant environmental preferences, mainly thermal and lighting, are maintained. The integrated automation enables a smart building to minimize its power and energy usage, taking into account the interaction among lighting, HVAC and plug loads. The proposed approach is validated by experimentation conducted on a simulated medium-sized office building modeled in EnergyPlus, which reflects an existing commercial building in Virginia, U.S. However, the proposed approach can be applicable to any type and size of commercial buildings.

2. Model of a medium-sized commercial building and its loads by type

This section summarizes the simulated medium-sized office building model used as a basis to develop the proposed approach. The simulated medium-sized office building model is based on the U.S. Department of Energy (DOE)'s medium-sized reference building model available in (DOE, 2011a), reflecting buildings in Virginia/Maryland area with the post-1980 construction. (Cui, Wu, Hu, Weir, & Li, 2016; Li, Wen, & Bai, 2016) have simulated these reference buildings in lieu of real buildings for model development and evaluation. This building was modeled in EnergyPlus version 8.3- a widespread building energy simulation tool – which provides more accurate peak electric load savings than baseline methods. EnergyPlus is a whole building energy modeling and simulation tool, which ensures integrated building and system analysis and can predict dynamic behavior of building systems