Energy and Buildings 121 (2016) 1–10

Contents lists available at ScienceDirect

Energy and Buildings

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

Demand response potential of ventilation systems in residential buildings

Sergi Rotger-Griful*, Rune Hylsberg Jacobsen, Dat Nguyen, Gorm Sørensen

Department of Engineering, Aarhus University, Aarhus C 8000, Denmark

ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form 22 March 2016
Accepted 23 March 2016
Available online 24 March 2016

Keywords:
Demand response
Smart grid
HVAC systems
Ventilation fans
Building energy management systems
Residential buildings
Ancillary services
Modelling
Simulation

ABSTRACT

Heating, ventilating and air conditioning (HVAC) systems in buildings are attractive assets to provide flexible consumption from the demand-side. This flexibility can be applied to balance the intermittent electricity generation of renewable energy sources. This paper assesses the demand response potential of ventilation fans in Nordic countries considering indoor climate conditions using a 12-storey building as test bed. First, a model of the ventilation system is proposed and evaluated for the test bed. The model presents good accuracy and generalisation potential. Second, the installation conducted to remote control the building fans is detailed. Third, the flexibility potential of the ventilation system in the test bed is analysed to provide ancillary services and prolonged load sheds. Experimental results show the need to aggregate several systems to provide ancillary services and the feasibility of prolonged load sheds without compromising the comfort of the residents. Fourth, the impact of aggregating ventilation systems is evaluated by simulations. Simulated results show that by aggregating buildings similar to the test bed in Aarhus (Denmark) it would be possible to provide 1.57 MW of power reduction. The trade-off for this flexibility is reducing the comfort of the residents and energy efficiency by overall consuming more energy.

1. Introduction

According to the International Energy Agency, in 2013, 67.4% of the electricity generated was based on fossil fuels thus contributing to CO_2 emissions [1]. One way of reducing the CO_2 footprint in the electricity generation is to increase the share of renewable energy sources (RES). Compared to traditional fuel-based power plants, some RES like wind turbines and solar panels cannot produce electricity on-demand (i.e., production depends on external factors like weather conditions). This implies a higher degree of complexity when balancing the electricity production with the consumption. In this scenario and without cost-effective storage solutions more flexibility in the demand-side is required.

Demand response can provide on the short run the flexibility needed to handle the higher penetration of RES. Demand response is a change on the electricity consumption by the end user in response to an external trigger (e.g., a price signal) [2]. Among all the demand response sources, buildings account for an important part of the total electricity consumption and therefore have a large flexibility potential. In a country like Denmark, 66% of the total electricity is consumed by buildings [3], while in the United States it accounts for 75% [4].

When analysing the electricity usage in buildings, it can be observed that heating, ventilating and air conditioning (HVAC) systems have an excellent potential to provide demand response for the following reasons: HVAC systems account for an important part of the total electricity consumption in buildings (e.g., 13.4% in the United States [5]); buildings' thermal capacity enables the storing of energy by pre-heating or pre-cooling the building [6]; part of HVAC systems are already partially automated by building energy management systems (e.g., 14% in the United States [7]). In consequence, many studies have focused on demand response provision through HVAC systems [8–11,4,12–19].

Some HVAC systems are complex and present diverse configurations depending on the final purpose: heating, cooling and/or ventilating. Most of the electricity consumed by these systems accounts for cooling the air and warming it up [16,4]. This air is then circulated using fans, which account for a lower electricity usage. The higher consumption in heating and cooling has led to a larger focus on HVAC temperature control [14,8,15,16,9,10,20], compared to HVAC fan control [4,11–13]. In contrast to temperature regulation, most fans can be controlled by variable frequency drives enabling fast load control [4]. Although HVAC control for demand

* Corresponding author.
E-mail addresses: srgr@eng.au.dk (S. Rotger-Griful), rhj@eng.au.dk (R.H. Jacobsen).

http://dx.doi.org/10.1016/j.enbuild.2016.03.061
0378-7788/

Nomenclature

γ	power exponent [–]
ω	airflow exponent [–]
A	room area [m^2]
A_D	DuBois surface [–]
C	indoor CO_2 concentration [ppm]
C_{out}	outdoor CO_2 concentration [ppm]
CV	coefficient of variance [%]
G	CO_2 flow generate indoors [(m^3 ppm)/s]
H	person height [m]
MAPE	mean absolute percentage of error [%]
MET	metabolic equivalent of task [met]
MSE	mean squared error [–]
N	rotational speed [rpm]
n	number of people in room [–]
P	power [W]
p_s	static pressure [Pa]
P_{fan}	fan power [W]
P_{ref}	power reference of fan [W]
$p_{s,ref}$	static pressure reference of fan [Pa]
Q	system airflow [m^3/s]
q_b	emissions airflow from building [m^3/(s m^2)]
$Q_{CO_2,gen}$	generated CO_2 [m^3/s]
q_L	leakage/infiltration airflow of a room [m^3/s]
q_p	airflow per person [m^3/(s person)]
Q_{ref}	system airflow reference [m^3/s]
q_{tot}	total airflow supplied to a room [m^3/s]
RQ	respiratory coefficient [–]
$S(k)$	time series seasonality
$T(k)$	time series linear trend
V	room volume [m^3]
W	person weight [kg]
x	linear model predictor
y	linear model response variable
AHU	air handling unit
API	application programming interface
CEST	Central European Summer Time
HTTPS	Hypertext Transfer Protocol Secure
HVAC	heating, ventilating and air conditioning
ICT	information and communications technology
PC	personal computer
RES	renewable energy sources
REST	representational state transfer
TSO	transmission system operator

response purposes is a common practice in commercial and industrial buildings in the United States, it is not in residential buildings in the Nordic countries. In Denmark, air conditioning penetration is low due to the cold temperatures and most of the heating is provided by non-electric sources (e.g., district heating). This has led to very few studies focusing in a country with these characteristics [8], in contrast to many studies done in regions with high penetration of air conditioning and electric heating [9,11,4,12–16,18,19].

This paper analyses and demonstrates the demand response potential of HVAC systems in a scenario without cooling and heating needs. By doing so, the flexibility potential of HVAC systems is reduced to control the ventilation fans. This flexibility is lower than in scenarios with air conditioning, where fan control indirectly affects temperature. Special attention is put into evaluating the provided demand response in terms of response time and event duration, thus considering indoor climate conditions and building regulations. In contrast to most studies [8–11,4,14–16], the results shown in this paper come from experiments in a real building. The test bed is a 12-storey residential building equipped with more than 3400 sensors located in Aarhus, the second largest city in Denmark. The ventilation system in this building has been integrated with an information and communications technology (ICT) system for remote control and monitoring.

The rest of the paper is organised as follows. The related work is described in Section 2. Section 3 provides an overview of HVAC systems and describes the model of ventilation systems. Section 4 presents the test bed and the upgrades implemented in the ventilation system for remote control. The model is validated in Section 5. The experimental results and simulated results are presented in Sections 6 and 7, respectively. The paper is concluded in Section 8.

2. Related work

2.1. HVAC control for demand response

In a demand response scenario, the normal operation of a ventilation system is modified to satisfy the demand response needs. However, this change may be counteracted by other components of the system (e.g., dampers' position) [10]. This makes demand response provisioning from ventilation systems a challenging task. The large diversity of HVAC systems leads to a large variety of control strategies for demand response provisioning. Examples of strategies are global temperature adjustment, duct static pressure control, water temperature control in the chillers, use passive thermal storage of the building and many others [10,20]. Despite this diversity, in the literature there are two mainstream development of HVAC control for demand response: temperature adjustment and fan control. The former and most common one uses the thermal inertia of buildings and it is suitable for slow and prolonged load changes. The latter enables a fast load change if the fans are equipped with variable frequency drives.

Erickson and Cerpa [9] claim savings of 20% of energy by regulating the temperature of a HVAC system in a simulated EnergyPlus building using occupancy predictions. In [16], the authors propose a controller that takes 15-min price signals and controls temperature in a simulated EnergyPlus building considering the comfort of the residents. The demand response potential of a HVAC system in a simulated Finnish household is discussed in [8]. In [14], the authors examine the interconnection between HVAC systems for demand response in a time scale of 30 min up to at most a few hours using different strategies in a co-simulation environment and claim a power reduction from 23% up to 47%, while maintaining occupant comfort according to ASHRAE Standard 55-2010.

The authors in [4] use a model to assess ancillary services provision by HVAC systems in commercial buildings. They defend that by using variable frequency drives 15% of the fan capacity can be used for regulation. The same authors use simulations to show that fans in commercial buildings can be controlled within 8 s notification time [11]. Zhao et al. [21] evaluate the capacity of commercial building HVAC systems to provide frequency regulation. Their results are originated from simulations using the performance based regulations dictated by PJM, a regional transmission organisation in the United States. In [13], the authors make experiments in a real commercial building where the duct static pressure is controlled. They use these data to construct a model and analyse the demand response potential. The authors in [12] claim to be the first to control the HVAC system in a real building for ancillary service provisioning. Their results show that by participating in the regulation market a commercial building could earn $1421 per year by controlling the fan speed and flow rate. More recently, the authors in [18,19] have done an experimental evaluation on chiller control for frequency regulation in a couple of buildings. The authors demonstrate that around 25% of the nominal power of the