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Investigation of demand response potentials of residential air conditioners in smart grids using grey-box room thermal model

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HIGHLIGHTS

- A grey-box room thermal model for indoor air temperature prediction is developed.
- Pre-estimation and scaling are made for accuracy and computational efficiency.
- Optimization algorithms, i.e. GA, PSO and TRA, are used for model identification.
- DR strategies of temperature set-point reset and precooling are evaluated.

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ABSTRACT

Over the last few years, the development of information and communication technologies has provided a great opportunity for the residential sector to take part in demand response (DR) programs in smart grids (SGs). Optimal load scheduling via home energy management systems (HEMSs) is a typical technique used to reduce the power consumptions during the DR events. One of the major challenges faced by the HEMS manufacturers and the electric utilities is the lack of an accurate yet convenient tool for predicting the power consumptions of residential homes, particularly the air conditioners, for decision-makings. The aim of this paper is to develop an accurate self-learning grey-box room thermal model and use it to investigate DR potentials of residential air conditioners (ACs). The readily available indoor air and outdoor air temperatures in today's HEMSs are used to train the room thermal model. The model parameters are pre-estimated and scaled to improve the optimization accuracy and computational efficiency. Three optimization techniques including trust region algorithm (TRA), genetic algorithm (GA) and particle swam optimization (PSO) are employed to identify the model parameters separately and their performances are compared. A case study shows that the room thermal model can accurately predict the indoor air temperature profile. Two types of DR strategies of residential ACs, i.e. temperature set-point reset and precooling, are then tested using the room thermal model and a simplified air conditioner energy model. Simulation results show that temperature set-point reset combined with precooling strategy can result in more than 26% power reduction during the DR hours on a typical summer day in Hong Kong, without significant change of thermal comfort.

1. Introduction

Smart grid is an intelligent electric system that integrates with advanced communication and control technologies, transforming the current grid to one that is cleaner and more efficient, reliable, resilient and responsive [1,2]. Demand response (DR), facilitated by smart grids, can achieve reductions in the peak loads, energy consumptions, and carbon emission [3–5]. Besides, it can facilitate greater penetrations of intermittently available renewable resources (solar and wind in particular) [6,7]. According to the U. S. Energy Information Administration, demand response programs provided 13,036 MW actual peak reductions in 2015 in total, and the residential sector provided 26% of the total peak reductions [8]. As indicated by Federal Energy Regulation Committee, it is the residential class that represents most untapped potentials for demand response, and the residential customers are able to provide over 45% of the potential impacts in 2019 [9]. Residential DR plays an important role in the potential DR resources [10–13]. Residential air conditioners (ACs), as the major contributors to the home electricity bills, have been attracting increasing interest in exploiting the DR potentials of residential homes.

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Nomenclature

A	area, m^2
AC	air conditioner
c	scaled thermal capacitance, ranging from 0 to 1
C	equivalent overall thermal capacitance, J/K
DR	demand response
EIR	energy input ratio of AC, the inverse of COP
ETP	equivalent thermal parameter model
f	radiative/convective split for heat gain
GA	genetic algorithm
$HEMS$	home energy management system
I	global solar radiation, W/m^2
OM	order of magnitude of parameter value
PSO	particle swarm optimization
Q	heat gain, W
r	scaled thermal resistance, ranging from 0 to 1
R	equivalent overall thermal resistance, K/W
S	AC on-off signal
SG	smart grid
$SHGC$	Solar Heat Gain Coefficient
T	temperature, °C
TRA	trust region algorithm
U	heat transfer coefficient, W/(m^2·K)
WWR	window-to-wall area ratio

Greek symbols

α	absorptance of surface for solar radiation
ζ	searching factor, ranging from 0 to 1
δ	dead band for AC control
σ	thickness, m
ρ	density, kg/m^3

Subscripts

cap	cooling capacity of AC
db	air dry bulb temperature
est	estimated values
ex	external
i	indoor air
in	wall internal surface
$inter$	internal
lb	lower bounds
m	internal thermal mass
nom	nominal operation condition
o	outdoor air
set	set-point
ub	upper bounds
w	wall
wb	air wet bulb temperature
win	window

Both electric utilities and smart home energy management systems (HEMSs) requires the predictions of power reductions of residential ACs to implement DR strategies. For the former, many influential decisions on grid operations are made based on the predicted power reduction, such as generation and reserve planning, dynamic electricity prices and payments to homes joining DR program [14,15]. Taniguchi et al. evaluated the effects of electricity saving measures on peak demand reductions in the Japanese residential sector on a region scale (5000 households) based on a bottom-up type model [16]. Widergren et al. discussed the design of the electricity rate, and simulated the DR resources at the distribution level where the residential consumers and household appliances can receive real-time pricing signals [17]. For the latter, the widely adopted optimal load scheduling methods for DR in the presence of dynamic electricity pricings are also developed based on the predication of AC power consumption. To determine the optimal balance between hourly electricity prices and the use of smart household appliances, Lujano-Rojas et al. proposed an optimal load management strategy which considered predictions of electricity prices, energy demand and renewable power productions [18]. Molina et al. developed an optimization methodology, which includes system identification, model-predictive control and genetic algorithm, to achieve an acceptable compromise between comfort and cost in the presence of dynamic electricity prices [19]. Room thermal models are necessary to predict the power consumption and power reduction of residential ACs.

Different types of room thermal models have been applied for residential DR purpose. Building simulation softwares, such as EnergyPlus in [20], and eQUEST in [21], were used to simulate the room thermal dynamics under different DR control strategies. A large amount of building parameters are required as inputs in the simulation softwares, which is difficult even for the newly designed buildings. Besides, it is extremely time-consuming when investigating the DR resources of a population of homes on a region scale. Another room thermal model is the widely-used equivalent thermal parameter (ETP) model, which simplifies the room thermal dynamics as a second-order electric circuit analog. Lu and Katipamula [22,23] used the ETP model to study the impacts of various residential air conditioner control strategies on electric distribution feeder load profile during the DR periods for a single residence and a number of residences separately. Based on the ETP model, Thomas et al. [24] proposed an intelligent residential AC system controller to provide optimal comfort and cost trade-offs for the residents. The ETP model was also adopted by Zhang et al. [25] to describe the thermal dynamics of each individual load and deal with a number of heterogeneous loads. Besides, GridLAB-D, an open-source power systems modeling and simulation environment, also uses the ETP model to simulate the AC energy consumptions during the DR events [26]. However, there are two main critical issues about the ETP model. First, the model is too simplified to consider the impacts of specific building features such as wall material, window arrangement, and internal thermal mass. Second, the values of the ETP model parameters were determined according to the room geometry and thermal parameters in a database developed over 20 years ago [27]. The room thermal parameters are only applicable to the residential buildings in the US. The architecture design and envelop thermal properties are very different from the high-rise residential buildings in modern cities like Hong Kong and Shanghai. The uncertainties of the parameters have significant impacts on the accuracy of the modeling results.

The present study aims to develop an accurate self-learning grey-box room thermal model and the associated parameter identification methods for investigating DR resources from residential air conditioners (ACs). Three major contributions are made in this study. First, we developed an accurate grey-box room thermal model for predicting the indoor air temperature under dynamic operating conditions. The model parameters can be learnt by making effective use of the data available in the today's smart in-home sensors. Second, we proposed pre-estimation and scaling approaches to pre-processing the model parameters, which help

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