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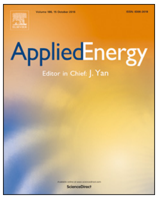

Price-responsive model-based optimal demand response control of inverter air conditioners using genetic algorithm

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HIGHLIGHTS

- A steady-state physical model of inverter air conditioners is developed.
- Inverter AC model is integrated with a control-oriented room thermal model.
- GA is used to search the optimal indoor air temperature set-point schedule.
- Sensitivity analysis on trade-off weightings in objective function is conducted.

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ABSTRACT

The rapid developments of advanced metering infrastructure and dynamic electricity pricing provide great opportunities for residential electrical appliances, especially air conditioners (ACs), to participate in demand response (DR) programs to reduce peak power consumptions and electricity bills. One of the biggest challenges faced by residential DR participants is the lack of intelligent DR control methods which enable residential ACs to automatically respond to dynamic electricity prices. Most existing studies on DR control of residential ACs focus on single-speed ACs. However, inverter ACs which have higher part-load efficiencies have been extensively installed in today's residential buildings. This paper presents a novel model-based DR control method for residential inverter ACs to automatically and optimally respond to day-ahead electricity prices. A control-oriented room thermal model and steady-state model of inverter ACs are developed and integrated to predict the coupled thermal response of the room and AC for the purpose of model-based control. Optimal scheduling of indoor air temperature set-points is formulated as a nonlinear programming problem which seeks the preferred trade-offs among electricity costs, thermal comfort and peak power reductions. Genetic algorithm (GA) is used to search the optimal solution of the nonlinear programming problem. Simulation results show that compared with the baseline case, the proposed model-based optimal control method can reduce the whole electricity costs and the peak power demands during DR hours while meeting thermal comfort constraints. Besides, sensitivity analyses on the trade-off weightings in the optimization objective function demonstrate that electricity costs, occupant comfort and peak power reductions are sensitive to the weightings and the use of the weightings is effective in achieving the best trade-off.

1. Introduction

Power imbalance is a critical issue faced by current electrical grids. The increasing penetrations of intermittent renewable resources, e.g. wind and solar, have made the imbalance situation worse. Buildings are responsible for around 40% of the total energy consumptions worldwide, and consume over 70% of the total electrical energy in the USA [1] and over 90% of the total electricity in Hong Kong [2]. As the major end-user of electricity, buildings have great responsibilities and potentials to provide peak power reductions during on-peak hours. Since heating, ventilation and air conditioning (HVAC) systems account for a large proportion of the total building electricity use, their power consumptions have direct impacts on power grids [2]. According to California energy demand report, HVAC systems are the major contributors to most of the peak power demands in summer in California [3]. Therefore, demand response (DR) management of building HVAC systems is considered as one of the most promising solutions to grid power imbalance issue in recent years. In commercial buildings, DR

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Nomenclature

A	area, m^2
AC	air conditioner
BAS	building automation system
C	electricity price
C	equivalent overall thermal capacitance, J/K
c	specific heat, J/K
DAP	day ahead electricity price
DR	demand response
E	energy consumption during a period
EEV	electronic expansion valve
GA	genetic algorithm
h	specific enthalpy, J/kg
HEMS	home energy management system
HTC	heat transfer coefficient
HVAC	heating, ventilation and air conditioning
J	cost function
K	coefficients of PID controller
MAE	mean absolute error
MAPE	mean absolute percentage errors
N	operating frequency of compressor motor, Hz
NTU	number of transfer unit
P	power consumption, W
P	pressure, Pa
Q	cooling capacity of AC, W
Q	heat gains, W
R	equivalent overall thermal resistance, K/W
RC	resistance-capacitance room thermal model
RMSE	root mean square error
RTP	real-time electricity price
T	temperature, °C
$\dot{m}$	mass flow rate, kg/s

Greek symbols

α	heat transfer coefficient
α	weighting of thermal comfort
β	weighting of peak power
ε	heat transfer effectiveness
η	compressor efficiency

Subscripts

c	condenser
comp	compressor
e	evaporator
ex	heat exchanger
ext	external surface of wall
i	inlet
in	indoor air
int	internal surface of wall
inter	internal heat gains
is	isentropic process
lb	lower bound
m	internal thermal mass
o	outdoor air/outlet
p	constant-pressure process
r	pressure ratio
ref	refrigerant
set	set-point
solar	heat gain from solar radiation
sur	surface
ty	typical
ub	upper bound
v	constant-volume process
w	wall
win	window

technologies such as use of building thermal mass [4,5] and thermal energy storage systems [6–8] have been adopted to reduce and shift power consumptions of large central HVAC systems. Central HVAC systems are normally managed by advanced building automation systems (BAS) and professional engineers, which enable them to fulfill automatic DR control. Residential ACs, particularly the inverter ACs, are still facing challenges to make automatic DR during on-peak hours.

To fully exploit the DR potentials of residential electrical appliances, advanced metering infrastructure such as smart meter [9] and home energy manage system (HEMS) [10] have been developed and implemented in many residential buildings, which provide great opportunities for residential ACs to make automatic DR. Smart meters enable residential end-users to receive dynamic electricity prices from electric utilities or third-party load aggregators. Two types of dynamic retail electricity pricings are widely used in the USA, i.e. Day Ahead Price (DAP) and Real-Time Price (RTP) [9]. DAP is usually calculated at hourly intervals and announced to the end-consumers one day ahead, while RTP is determined every 5 minutes based on the current electricity supply and demand of grid. In order to reduce electricity costs in the dynamic electricity pricing environment, residential DR participants can reduce the electricity use during high-price periods and shift the electricity use to low-price periods. Automatic DR control methods are essential for residential electrical appliances to respond to dynamic pricing. Smart HEMSs facilitate the implementation of automatic DR control methods and strategies for residential appliances including ACs. Many studies have been conducted on DR control of residential electric appliances in the dynamic pricing environment. The commonly used DR control method for residential ACs is indoor air temperature set-point reset based on the dynamic electricity prices [11–16]. Chen et al. [11] used stochastic optimization and robust optimization approaches to optimize the operation scheduling of six typical residential appliances based on real-time electricity prices. The objective was to minimize the whole-day electricity payment without largely sacrificing thermal comfort. A mixed-integer linear programming problem was formulated and solved by Hubert et al. [12] to minimize electricity costs. Their work showed that advanced scheduling controllers implemented in HEMS were valuable to fully achieve the DR benefits. Lujano-Rojas et al. [13] proposed an optimal energy management strategy for residential energy system consisting of renewable power generations and electrical vehicles based on real-time electricity prices. The optimized operation scheduling for household appliances and electrical vehicles reduced the electricity bills by 8%–22% on typical summer days. Thomas et al. [14] developed an intelligent AC controller which can provide the optimal comfort and cost trade-offs for the residents by scheduling the AC on/off status. Li et al. [15] investigated and compared different DR strategies for residential ACs under different dynamic electricity pricings and environmental conditions based on eQUEST simulations. Yoon et al. [16] proposed a price-responsive controller for residential HVAC system which enables to reset temperature set-point when the retail price is higher than the preset price. Simulation results showed that the DR controller can provide up to 10.8% energy cost savings and 24.7% peak power reductions.

Although DR control methods of residential AC have been extensively studied, the ACs considered in previous work were all single-speed ACs which only allowed on-off control. The on-off controlled ACs have a big disadvantage of undesired current peaks during state transitions [17]. The single-speed ACs are also gradually replaced by inverter ACs which have gained an increasing market share in recent