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Soft-repair technique for solving inherent oversizing effect on multiple rooftop units in commercial buildings

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ABSTRACT

Rooftop packaged air-conditioning units (RTUs) have been intensively utilized in commercial buildings for providing space heating and cooling. They serve over 60% of the commercial building floor space in the U.S. Specifically, oversizing is an inherent issue practically caused by over design of mechanical engineers. With field test studies, oversizing can be up to 100% leading to high energy penalty. Although there are locally advanced control technologies utilized to improve the overall efficiency performance of RTUs, they are invasive approaches to interrupt normal operations and require experienced service teams for preventative maintenance causing high cost installation and service costs. The article proposes a novel and non-invasive methodology for permanently reducing the oversizing caused by non-optimal design or faulty design called “soft-repair”. The technique composes of coordination control and oversizing analysis to ultimately eliminate the fault impact without retrofitting original control. Control algorithms are systematically developed to mainly reduce oversizing effect utilizing simplified instantaneous building load for approximately quantify actual building load. With the control algorithm tested by a building simulation platform, the oversizing effect can be decreased at least 30% by comparing oversizing parameter signature of the original oversizing system with the improved results of soft-repair implementation because a suitable number and time operations of RTUs are automatically computed based on the actual building load and the soft-repair algorithm. With the decrease of the oversizing effect and energy penalty, the improve results lead to energy savings and extended life cycle of compressors, condenser fans and supply fans.

1. Introduction

Rooftop packaged units (RTUs) consumed approximately 60% of total energy to provide both cooling and heating systems for commercial buildings in the U.S. Specifically, they serve nearly 50% of all cooling conditioned commercial floor space in the U.S. [1]. As a result, proper sizing and operations of RTUs lead to significant energy savings. However, practically, oversizing is an inherent issue in typical heating, ventilation and air-conditioning (HVAC) systems because at least 15% oversizing of actual building load is acceptable for HVAC designers in order to ensure adequate cool and heat in the hottest and coldest period of each building location. Based on site surveys in Ref. [2], 40% of surveyed RTUs were oversized more than 25% of an actual capacity. Furthermore, with field test studies, oversizing can be up to 100%; Woradechjumroen et al. [3] investigated 268 RTUs located in 12 stores at different climates in the U.S; the over-sized capacity of the RTUs has an average value of 84% for cooling and 299% for heating. These calculated oversizing capacities cause the highest peak energy penalty around 226.41 kW in a cooling mode and 1375.99 kW in a heating mode. In addition, the oversizing problem lead to shorter life cycles of RTUs since the oversized RTU compressors are frequently cycled based on on-off control operations. This problem also results in higher operation cost due to the lower efficiency from the improper operation of the RTUs. Utilizing multiple oversized RTUs in light commercial buildings with open spaces, such as big-box retail stores and low-rise cubicle offices, non-coordinated local control will incur simultaneous cooling and heating causing waste energy. Solving the non-synchronized functions between each local controller and sub-system or between coupled systems, coordination control or supervisory control based on model predictive control (MPC)

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Nomenclature

k_{env}	Building envelop load coefficient (W/°C)
n	Cycling rate (cycle per hour)
N_C	A number of required RTU compressors
N_f	A number of required RTU fans
OAT	Outdoor air temperature (°C or °F)
OA	Outdoor air
PLR	Part load ratio
$P_{startup,k}$	Startup power multiplier of kW (dimensionless)
P_s	Supply pressure (Psi)
P_z	Zone population (person/1000 ft^2)
$\dot{Q}_c$	Instantaneous cooling load (W or Btu/hour)
$\dot{Q}_{gen}$	Generated load in z zone (W or Btu/hour)
$\dot{Q}_h$	Instantaneous heating load (W or Btu/hour)
R_a	Outdoor airflow rate required per unit (cfm/ft^2)
R_c	Supply airflow rate required per unit ton of cooling load (cfm/ton)
R_h	Supply airflow rate required per unit ton of heating load (cfm/ton)
R_p	Outdoor airflow rate required per person (cfm/person)
RTF	Runtime fraction
T	Temperature (°C or °F)
$T_{sp,c}$	Cooling set-point (°C or °F)
$T_{sp,h}$	Heating set-point (°C or °F)
ΔT_{heat}	Differential heating temperature (°C or °F)
ΔT_{cool}	Differential cooling temperature (°C or °F)
ΔT_{ij}	Differential temperature in a zone (°C or °F)
Δt_{ij}	Differential time in a zone (minutes)
$\Delta t_{on,ij}$	Differential on-time in a zone (minutes)
$\Delta t_{off,ij}$	Differential off-time in a zone (minutes)
$\dot{V}$	Volume flow rate (CFM, m^3/s)
$\dot{V}_{oa}$	Outdoor ventilation (CFM)
$\dot{V}_c$	Minimum airflow of heating (CFM)
$\dot{V}_h$	Minimum airflow of cooling (CFM)
$\dot{V}_t$	Whole conditioning space (CFM)
$\overline{V}_{RTU}$	Average airflow rate (CFM)
$\dot{V}_v$	Minimum airflow rate for ventilation (CFM)
β	outdoor damper ratio

Subscript

amb	Ambient temperature
b	Balance temperature
i	RTU location at row i
j	RTU location at column j
k	Numbers of RTUs
l	A number of RTUs in row i
max	Maximum value
min	Minimum value
m	A number of RTUs in column j
oa, actual	Actual outdoor air
oa, required	Required outdoor air

strategies have been continuously proposed in order to predict the future states of a control inputs [4–16]; the coordinated and computed inputs are mainly utilized to minimize a cost objective function over the window moving period in the presence of the predicted model uncertainties and function constraints. However, Most of the previous MPC articles are mainly utilized for energy savings or building performance improvement in large-scale buildings which are served by chiller systems. A few coordination control methods have been developed for many small-and medium-scale commercial buildings such as retail stores with open spaces served by multiple RTU functions; one of them has been recently proposed based on the model-based optimization algorithms of coordination control in a restaurant; it is focused to minimize power and maintain thermal comfort over a short prediction horizon in terms of "plug and play concept" because additional sensors are not required for the control implementation [17]. Although this research can accomplish the energy savings up to 20%, the algorithms are not mainly develop for reducing the oversizing effect and some RTUs are not improved for the oversizing issue due to research assumptions. Currently, the coordination control research of multiple RTUs could not penetrate HVAC market; several points can be further challenged for this control application.

In terms of recent commercialization, although there are low-level control technologies [18–22], such as variable feed drive, multi-stage compressor control and fan-speed control, utilized to improve the oversizing issue of RTUs, they are invasive approaches which cause interrupt normal operations and cannot be switched back to the original control performance. The design, installation and preventive maintenance of those invasive control solutions require experienced teams causing high cost installations and service costs with returning on investment (ROI) being more than 3–5 years depending on the type of a building. The two significant projects were conducted economic analysis for the ROI approximations in terms of simulation [19] and field test implementation [22]. For the simulation assessment, the controller costs of the four building prototypes (small office, stand-alone retail store, strip mall and supermarket building model) were analyzed and summarized for 22 control combinations [18]. However, some combinations are not in product vendors for the field assessment. For the engineering point of view, the field test results were further conducted as the ongoing project; four commercial products were preliminarily investigated their functions and one of them was selected for the implementations of 66 RTUs [23]. The controller cost analyses of the field assessment are tabulated in Table 1:

From Table 1, the controller costs are varied according to the variable frequency drive (VFD) of RTU supply fan size. The energy savings were conducted by comparing the conventional control with the advanced control function. The conventional control was set for constant supply-fan speed at 100% when a mode operation is on-status without the utilization of the air-side economizer integrated with mechanical cooling and the demand-controlled ventilation (DCV). Meanwhile, the supply fan was operated at different speeds based on VSD setting which was synchronized with the air-side economizer based on differential dry-bulb temperature controls and the enabled DCV. These implementations leaded to energy savings between 22% and 90% depending on building operators experience and original RTU performance conditions. As a result, average ROI periods were 6, 3, and 2 years for the different utility rates of 0.05 $/kW h, 0.10 $/kW h, and 0.15 $/kW h, respectively. However, preventive maintenances could be increased and are not currently considered because of required experienced teams for the advanced energy saving control leading to higher service costs.

Functionally, the advanced retrofitting solutions are still individual control without analyzing and solving the inter-zone