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

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Highlights

- The article proposes a novel and non-invasive methodology for permanently reducing energy penalty caused by non-optimal design.
- The technique uses coordination control and oversizing analysis to minimize the fault impact tested by a building simulation platform.
- The technique leads to energy savings and extended life cycle of compressor, condenser fan and supply fan without original system interference.

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.

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) strategies have been continuously proposed in order to predict the future states of a control inputs [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [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], [19], [20], [21], [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 interactions or temperature distribution between zones [24], [25], [26], [27], [28], [29], [30]. Additionally, they cannot eliminate problems such as simultaneous cooling and heating and non-coordinated control of multiple RTUs. To eliminate non-intrusive functions of the aforementioned technologies, this current article proposes the novel technology called “soft-repair” which utilizes adaptive control strategies so as to temporarily minimize the fault impact until the receipt of actual physical repair or ultimately eliminate the fault without any further physical intervention [31], [32]. With the general definition, the authors mainly propose the soft repair technique composing of coordination control and simplified building loads to permanently reduce inherent oversizing effect on multiple RTUs caused by non-optimal design process (oversizing). The algorithms can be systematically designed based on 5 steps to automatically compute control inputs for sequentially staging the on-off control of each RTU; the implementation and utilization of the proposed technique is explained in step 6.

To automatically select a suitable model operation (cooling, heating or economizing mode) or appropriate control inputs corresponding to outdoor air temperature (OAT) variations, building load or zone temperature models have been developed for future prediction of the building or system performance [33], [34], [35], [36], [37], [38], [39], [40], [41], [42]. Most of the prior researches are based on dynamic models or transient temperature equations, whereas the soft-repair algorithms of the present article are mainly developed to test the feasibility of the non-invasive control solution. As a result, easy-to-implement building load prediction model is more suitable for reducing the complex computation process.

To address this point, the simplified instantaneous building model developed by Woradechjumroen and Li [43] is based on steady-state heat balance equations, and is utilized in the algorithms; the physical parameters compose of a balance temperature, cooling and heating set-point, and outdoor air temperature and envelop load coefficient of an enclosed structure. To implement and test the soft-repair algorithms, the building simulation platform is developed based on Heat, Air and Moisture Laboratory (HAMlab) [44], [45], [46] implemented on Simulink. The results of the proposed algorithms are compared with the benchmark case, which uses typical on-off control with one-stage fan and compressor operation with 24h in a store operation, in terms of reduced cycling rate (n), increased runtime fraction (RTF) and part load ratio (PLR).

The study is organized as follows: the related backgrounds of soft-repair rationale, multiple RTU operations and simplified instantaneous building load are briefly described at first. Secondly, the development of soft-repair algorithms are systematically introduced and explained. Next, a building prototype with HVAC components is detailed and further used as the simulation platform for implementing the two case studies consisting of the soft-repair implementation and a benchmark operation. Before coding the coordination control procedures, fan and compressor control sequences are designed in section 5. After that, results of the proposed technique are evaluated and discussed in terms of oversizing signature parameters (n, RTF and PLR). At the end, the contribution of the findings is briefly discussed.

Section snippets

Backgrounds

Since soft-repair concept is developed for self-maintenance to enhance decision makings of original process recovery in terms of reducing system intervention when faults are diagnosed, differently diagnosed faults lead to distinguish algorithms. To design this process efficiently, a number of fault types or system problems should be identified. This section briefly reviews and synthesizes significant backgrounds associated with faulty operations of multiple RTUs and instantaneous building loads …

Soft-repair algorithms

According to the oversizing analysis by Woradechjumroen et al. [3], the characteristics of oversizing issue are observed from RTF, n and PLR of RTU compressor operations. The average RTF of some RTUs is much smaller than 1.00 at the design temperature condition; it means oversizing issue being very severe. As a result, the on-time period of the RTUs in this case should be adjusted longer while maintaining thermal comfort of the zones. For the routine operations in terms of interactions among …

Building information description and building simulation platform

To estimate the potential energy savings of the soft-repair approach, the energy use of a prototypical building, which predominantly use packaged units for heating and cooling, is simulated in different periods of the same artificial data. The selected building example, locations, and climate are discussed in this section. …

Fan and compressor control sequences

A group of RTU is designed based on the estimated numbers of required fans and compressors for operations to provide sufficient cooling and heating when OAT changes. The example of the RTU selection is demonstrated for the cooling mode utilizing the simulated data duration from July 1 to July 3. For these three days as shown in Fig. 5, the cooling mode is required only for the periods $(\dot{V}_t = \dot{V}_c)$. A number of RTUs are varied from 1 to 4 at the maximum OAT (36.7 °C). Since part load conditions …

Soft-repair for solving oversizing effect

For inherent oversizing effect due to overdesign of building load, the effect can be analyzed in terms of RTF, which is the ratio of on-time RTU compressor duration to the cycling period (the summation of on-time and off-time period) as shown in Eq. (15). $RTF = \frac{l_{on}}{l_{on}+l_{off}}$

With this equation, the soft-repair technique is designed to extend longer on-time periods, while reducing an off-time period of each compressor cycle. Using this strategy, a number of the compressor cycles are reduced. In the …

Conclusion

Oversizing is an inherently faulty design that could be up to 100% because related engineers or HVAC designers have followed guidelines and used rule of thumb without experiences. The current solutions used for a RTU are non-coordinated control function and invasive technology leading to cost-prohibitive and original system intervention, respectively. To solve the limitations, with the developed model, 6 steps are systematically designed to perform the proposed soft-repair algorithm as the …

Recommended articles

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