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Procedia Computer Science 86 (2016) 341 – 344

Procedia Computer Science

2016 International Electrical Engineering Congress, iEECON2016, 2-4 March 2016, Chiang Mai, Thailand

Fault Detection and Diagnosis Process for Oversizing Design on Multiple Packaged Air-conditioning Units

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Abstract

Heating, ventilation, air-conditioning and Refrigeration (HVAC&R) systems are seldom designed or commissioned properly. The situation leads to abrupt or degradation faults resulting in inefficient energy uses, excessive energy consumption and high service costs. To solve these aforementioned problems, fault detection and diagnosis (FDD) is utilized to firstly detect any abnormal conditions of a system and then diagnoses and determines their causes. In order to apply this concept in HVAC oversizing designs, this paper proposes the state-of-art procedure of a FDD procedure for analyzing the inherently faulty design (oversizing) of multiple packaged air-conditioning units used to supply cooling for an open space in light commercial buildings. A generic process of FDD for a packaged unit is briefly introduced to efficiently design FDD algorithms and to illustrate an overview picture for new researchers in FDD areas. In the procedures, compressor statuses, time-on and time-off operations and outdoor air temperatures are recorded by means of the on-board controller of each machine unit. These physical and electrical monitoring data are applied to diagnose and evaluate oversizing level in terms of runtime fraction (RTF) and cycling rate (N). Eventually, an adaptive control is designed and implemented to enhance process recovery for soft-repairing and permanently reducing fault effect caused by oversizing without intervening system operations (non-invasive technology).

Keywords: Fault Detection and Diagnosis; Multiple Packaged Air-conditioning Units; Oversizing, Process Recovery; Runtime Fraction

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doi:10.1016/j.procs.2016.05.092

1. Introduction

Packaged air-conditioning units or rooftop units (RTUs) are intensively used to provide heating or cooling for thermal comfort purpose in the U.S. At least around 2 problems occur in routine operations of each unit [1]. These mentioned fault examples are caused by routine operations, field commissioning, installation and maintenance. To prevent these happenings, automated fault detection and diagnosis (FDD) has been intensively developed as embedded intelligence for two main reasons: improved safety (e.g. nuclear power plant, aircraft and chemical process plant) and decrease of operational cost in terms of service and utility costs (HVAC&R). In the first objective, safety is mainly concerned, so expensive sensors and electronics can be utilized within FDD to achieve this goal. Meanwhile, ensuring safety is not the first priority in HVAC&R applications; it is mainly used to improve productivity in terms of equipment efficiency and better thermal comfort and to reduce operating costs and potentially schedule maintenances. Conducting the second goal on HVAC&R systems, low-cost sensors, on-board controller data and manufacturers' data are used to efficiently develop virtual sensors for extending limited measurement data and for physical reducing sensor costs to monitor the health of equipment, diagnose problems, and recommend service. FDD are multi processes performing as a series of three distinct functional procedures including: fault detection, fault diagnosis and process recovery, in which fault diagnosis is combined fault identification with fault isolation, and process recovery is involved with fault evaluation, decision and action as shown in Fig.1.

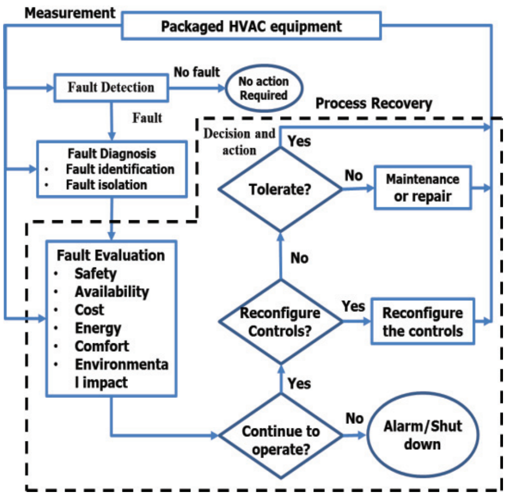

Fig. 1 Generic procedure of FDD to unitary HVAC equipment

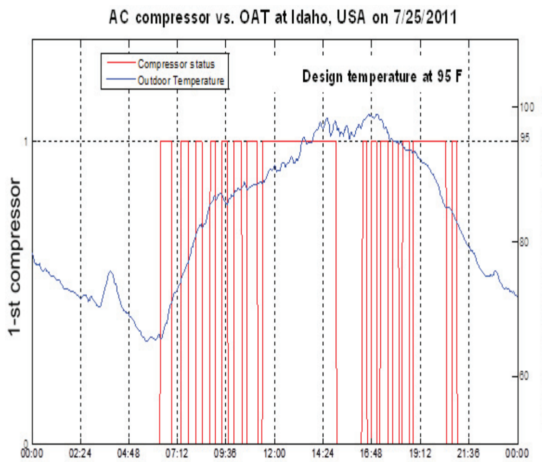

Fig. 2 Oversizing characteristics of a single-stage oversizing RTU compressor

Generally, faults in a packaged air-conditioning unit can be classified into abrupt faults (hard faults or failure) and degradation faults (soft faults). The first type happens immediately without system warning from conventional sensors; it is required to stop a process for an immediate repair such as compressor failure, control related faults and electrical faults. Meanwhile, soft faults are caused by non-optimal design and fault operations; they are not cost effective to be repaired immediately if the severity level is not high enough resulting in degraded system performance, but allow continued operation of the system. For example, there are oversizing, faulty control and typical hardware faults (e.g. incorrect refrigerant charges, drifted sensors, non-condensable, liquid-line restriction, evaporator fouling and condenser fouling). The impact of non-optimal design and faulty operations can be minimized or mitigated by adaptive controls called "soft-repair" before they are physically repaired. Most previous researchers have been continuously considering the typical hardware faults to protect later catastrophic equipment failure. Literature indicates that a few researches considered faults occurred by unsuitable design or oversizing design which is inherent behavior because at least 25% of actual cooling load are acceptably over designed to ensure adequate cool and heat in the hottest and coldest period by HVAC designers [2]. However, from field data analysis, oversizing can reach to around 100% [3]. This paper systematically presents the state-of-art process of a FDD procedure for analyzing the inherent oversizing of multiple RTUs; the process briefly introduces soft-repair algorithm as non-intervention in process recovery to remove the oversizing effect. The soft-repair is an innovative technique to enhance original process recovery without stopping the process monitoring loop.

2. Methodology

Using BACnet, a data communication protocol for building automation and control networks, the weather data and RTU performance data can be recorded and cleaned as follows:

1. Timestamps of compressor start time (t_{start}) and stop time ($t_{stop)}$ are recorded
2. Average outdoor air temperatures (OAT) are obtained in °F or °C).
3. The status records of RTU Compressors at timestamps (1 = turned on, 0 = turned off).
4. The selected design condition of OAT in each location is based on ASHARE Fundamentals [4]. For example, annual cooling 1% DB/WB is used to specify peak load conditions of the retail store I located in Idaho, USA as depicted in Fig. 2; OAT ranges being higher than 95 °F (35 °C) are peak load conditions for analyzing oversizing. If a compressor is designed properly, the compressor seldom cycles automatically. In contrast, an oversized compressor will cycle frequently during the same OAT range (> 95 °F or 35 °C) as illustrated in Fig. 2.

Table. 1 Equation and parameters for oversizing diagnostics

Parameters	Equations		Units
l_{on} (duration of on-status of a compressor)	$l_{on} = \left\| t_{start} - t_{stop} \right\|$	(1)	hour
l_{off} (duration of off-status of a compressor)	$l_{off} = \left\| t_{start}(next\ cycle) - t_{stop} \right\|$	(2)	hour
l_{cycle} (total duration for a cycle)	$l_{cycle} = l_{on} + l_{off}$	(3)	hour
N (cycling rate or a number of cycles occur in a hour)	$N = l / l_{cycle}$	(4)	cycle per hour
RTF (runtime fraction)	$RTF = l_{on} / l_{cycle}$	(5)	dimensionless

In step 1 of oversizing detection and diagnosis, based on the above oversizing behavior in terms of compressor operations, Table 1 tabulates all equations for oversizing diagnostics. Three durations of each compressor cycle in Eq. 1, 2 and 3 are used to calculate the two parameters (N and RTF) in Eq. 4 and 5 which can be used to diagnose oversizing signature. If RTF is closed to 1 and N is low, it shows rightsizing signature. Conversely, if N is high and RTF is low, it is oversizing signature. In step 2 of process recovery through the soft-repair algorithm, after conducting FDD, diagnosed oversizing results in high energy penalty[3], shorter life cycle of a RTU, lower efficiency and excessive energy consumption in terms of simultaneous heating and cooling. To keep continuing the operations of multiple RTUs while reducing oversizing effect without intervention, soft-repair is designed as an adaptive control to reconfigure sequencing operation by using the equations in Table 2. Since traditional RTU control is non-coordinated control, simplified instantaneous cooling ($\dot{Q}_c$) model was developed to compute actual total load and further determine by Eq. 8 in a whole open space of the light commercial building [5]. In step 2 of process recovery, applying Eq. 6, 7 and 8, total airflow rate can be computed. Then, the ideal minimum number of operating fans (N_i) is determined by Eq. 9 and 10. To increase essential load of each zone operation for reducing oversizing and to reduce fan power consumption, $\beta_{oa,required}$ is calculated by Eq. 11. Ni with calculated $\beta_{oa,required}$ of operating fans are enabling in a sequential order in order to mainly maximize comfort and indoor air quality in each zone corresponding to the agreement between cooling set point and measured zone temperature (Eq. 12). In addition, the decision-making procedure will be performed in a period which is determined by the occupied hours; 30 minutes could be the default of time operation to stop each fan and 5 minutes could be the default operating time to start a descending order of N_i. Finally, all the compressor(s) are started if fan status is on and a mode operation equals to cooling.

Table. 2 Equation and parameters for the soft-repair algorithm

Parameters	Equations or conditions		Units
$\dot{V}_t$ (total airflow rate)	$\dot{V}_t = MAX(\dot{V}_v,\ \dot{V}_c)$	(6)	CFM
$\dot{V}_v$ (minimum outdoor airflow rate)	$\dot{V}_v = R_p P_z + R_a A_z$	(7)	CFM
$\dot{V}_c$ (minimum airflow rate for cooling)	$\dot{V}_c = R_c \dot{Q}_c$	(8)	CFM
N_i (ideal minimum number of operating fans)	$N_i \approx \dot{V}_t / \bar{\dot{V}}_{RTU}$	(9)	dimensionless
$\bar{\dot{V}}_{RTU}$ (average RTU flowrate)	$\bar{\dot{V}}_{RTU} = \frac{1}{l \times m} \sum_{i}^{l} \sum_{j}^{m} \dot{V}_{ij}$	(10)	CFM
$\beta_{oa,required}$ (required outdoor air ratio)	$\beta_{oa,required} = \dot{V}_v / \dot{V}_t$	(11)	dimensionless
ΔT_{ij} (zone air temperature offsets)	$\Delta T_{ij} = T_z - T_{sp,c}$, cooling	(12)	°F or °C
Mode operation	$\text{mode}=\begin{cases} \text{cooling} & if\ \ \dot{V}_t = \dot{V}_c \\ \text{econimizing} & if\ \ \dot{V}_t = \dot{V}_v \end{cases}$		dimensionless

3. Results

For the case study, the building simulation platform (a retail store) using the artificial weather in Omaha, Nebraska USA was developed as the example. The building is divided into 8 zones with the very thin and low resistant interior walls (instead of virtual walls in the real building). A RTU is used to supply cooling or heating in each zone. Each RTU is diagnosed by step 1 and is oversized around 80 to 100%. After implementing the process recovery in step 2, oversizing can be reduced between 30 and 66%.

4. Conclusion

This paper proposes the state-of-art procedure of a FDD procedure for diagnosing oversizing of multiple RTUs in light commercial buildings. In step 1, the monitoring data are applied to diagnose rightsizing and oversizing signature using RTF and N. Then, process recovery in step 2 applies the adaptive control for permanently reducing oversizing effect up to 66% when the algorithm was tested in the building example without system intervention.

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