Measure Information Template –

Fault Detection and Diagnostics for Air Handling Units and VAV Boxes

2008 California Building Energy Efficiency Standards

PIER Program - EnergySoft, LLC February 6, 2006

CONTENTS

Overview

Description	Maintenance problems with built-up air handlers and variable air volume boxes are often not detected by energy management systems because required data and analytical tools are not available. Because of the large volume of data requiring analysis it is most practical to conduct the analysis within the distributed unit controllers. Researchers at National Institute of Standards and Technology (NIST) have developed diagnostic rules for air-handling units (AHU) and variable air volume (VAV) boxes. The Fault Detection and Diagnostic (FDD) system described here will provide operational performance data to the energy management system, allowing early correction of mechanical system faults.
Type of Change	It is proposed that the FDD technology be incorporated into the Standards as both a Compliance Option in the Nonresidential Performance Method, and also as a feature related to the Acceptance Requirements. Two documents will require changes to incorporate this feature. Section 3 of the Nonresidential ACM Manual will require an additional section describing this feature, and Chapter 8 of the Nonresidential Manual where the Acceptance Requirements are described. In addition, software vendors will need to modify their ACM products to incorporate this feature, and to incorporate the appropriate messages on the PERF-1 form identifying both the feature, as well as the requirement for field verification via the Certificate of Acceptance.
Energy Benefits	The most obvious benefit of this feature will be long term energy savings on air handlers and VAV boxes due to optimum operation. Since air conditioner operation is one of the bigger energy use components during peak demand periods, the primary savings from this measure will occur during the peak demand periods. The potential for savings will be in several areas of building energy use. Fan power consumption will be reduced due to proper operation of the air handler, as well as VAV boxes that are responding correctly to zone demand requirements. Cooling energy will be reduced due to proper operation of the VAV boxes since a VAV box that is providing too much air to a zone will end up overcooling the zone. This then results in wasted energy on the heating side, since the reheat coil will then need to be activated. In addition, pumping energy usage will be reduced as a result of not having to pump hot water out to the reheat coils.
Non-Energy Benefits	Two primary non-energy benefits result from the use of the FDD technology. The first will be lower operational costs. Clearly, by maintaining optimal performance of the system, energy cost savings will occur over the life of the system. The second area of impact will be equipment life. By maintaining operational peak efficiency, the life of the system will be extended.

Environmental Impact	No perceived negative environmental impacts will result from this technology.
Technology Measures	Measure Availability and Cost NIST worked with three major building control manufacturers to embed these rules in their respective controller products using the native programming language of each. A fourth manufacturer recently expressed interest in the next phase of development, which will entail testing at dozens of facilities to prove the reliability of the algorithms in different HVAC systems and facility types. It is anticipated that this technology will add little initial cost to the system. However, there will be some expense in the commissioning of the system and training of onsite personnel. Useful Life, Persistence and Maintenance The FDD technology is designed to last the life of the equipment.
Performance Verification	The only way to assure installation of this measure is via the Acceptance Requirements. The most obvious parallel would be DCV controls in the 2005 Standards. While building departments are responsible for verifying the correct specification of this feature, final verification and commissioning occurs via the MECH-6-A Acceptance Certificate. One of the benefits of the FDD, however, is the ability to verify proper equipment performance, including such features as the economizers. Therefore, it would be recommended that the MECH-4-A and MECH-7-A be modified to simplify functional testing when this measure is included. Installer verification would then be simplified to the task of proper calibration and operation of the FDD feature, as opposed to the system itself.
Cost Effectiveness	A payback has yet to be determined for this FDD technology.
Analysis Tools	The current reference method, DOE-2.1E is proposed to be used as the basis of determining savings for this measure, although the procedures developed in this measure template could be applied to any certified Alternative Calculation Method. One of the problems that we have with our analysis tools is that they assume a perfectly functioning building. This technology demonstrates that, in reality, we are being way too generous with this assumption as regards the HVAC system. However, the current nonresidential reference method can be used to model a reasonable representation of this “broken” HVAC system. In fact, procedures are already in the Standards for modeling of TXV valves using the same concept. The system without the TXV valve is modeled as using more energy than the system with the TXV valve. It is recommended that we apply similar concepts to the FDD feature.

Relationship to Other Measures	No other measures are impacted by this feature in the modeling.

Methodology

Since current practice in the industry is not to utilize FDD technology, and field data has shown that a high percentage of AHUs and VAV boxes have one or more faults, the baseline building assumption will include HVAC systems that do not include FDD. When the Standard building includes Air Handling Units, the economizer will be assumed to have a performance degradation of 10%. Thus, the maximum outside air capability of the economizer will be 90%. In addition, if the Standard building includes VAV boxes, a 10% degradation factor will be assumed. The minimum airflow ratio of the VAV box, which is typically 30%, will be increased to 33%. Thus, these components are assumed to be “broken” in the same fashion as we do with TXVs.

If the proposed building includes the FDD, the economizer performance would be restored to the normal 100% position and the VAV boxes, if present, would operate at their as designed minimum flow ratio.

In regards to the 10% degradation factor related to economizers, a conservative value was chosen. A field study on 503 rooftop units done by the New Buildings Institute (NBI) (see reference material at the end of this report) showed that 64% of the economizers to be faulty. This study includes 215 units surveyed by the California Energy Commission. Estimates in this report of energy savings by repairing the economizers were a 25% savings.

Note that this measure is not being proposed as a mandatory measure, nor as a prescriptive requirement. It is being proposed as a compliance option for building owners who choose to incorporate this feature. Given the large failure rate shown in the NBI report, and the fact that all sites that incorporated the FDD in the PIER study benefited, this measure offers excellent savings potential to building owners.

Analysis and Results

AHUs

The basis for the fault detection methodology is a set of expert rules used to assess the performance of the AHU. The tool developed from these rules is referred to as APAR (AHU Performance Assessment Rules). APAR uses control signals and occupancy information to identify the mode of operation of the AHU, thereby identifying a subset of the rules that specify temperature relationships that are applicable for that mode. The two main mode classifications are occupied and unoccupied. The 5 operating modes are summarized below:

- Mode 1: heating
- Mode 2: cooling with outdoor air
- Mode 3: mechanical cooling with 100 % outdoor air
- Mode 4: mechanical cooling with minimum outdoor air

- Mode 5: unknown

Because the direct digital control (DDC) output to the actuators of the heating and cooling coil valves and the mixing box dampers are known, the mode of operation can be ascertained. A fifth mode of operation referred to “unknown” operation has been defined and listed above. The unknown mode applies to the case in which the AHU is running in an occupied mode, but none of the control output relationships defined for Modes 1-4 are satisfied. The unknown mode could be associated with mode transitions and/or with faulty operation such as simultaneous heating and cooling. Once the mode of operation has been established, rules based on conservation of mass and energy can be used along with the sensor information that is typically available for controlling the AHUs.

VAV Boxes

The challenges presented in detecting and diagnosing faults in VAV boxes are similar to those encountered with other pieces of HVAC equipment. Generally there are very few sensors, making it difficult to ascertain what is happening in the device. Limitations associated with controller memory and communication capabilities further complicate the task. The number of different types of VAV boxes and lack of standardized control sequences add a final level of complexity to the challenge. This set of constraints is counterbalanced by the fact that VAV boxes are much more numerous than other pieces of HVAC equipment. For instance, buildings may have ten to fifteen times more VAV boxes than air-handling units. Hence, maintenance staffs would clearly benefit from a tool that assisted them in monitoring VAV box operation.

The needs and constraints described above have led to the development of VAV Box Performance Assessment Control Charts (VPACC), a fault detection tool that uses a small number of control charts to assess the performance of VAV boxes. The underlying approach, while developed for a specific type of VAV box and control sequence, is general in nature and can be adapted to other types of VAV boxes.

APAR and VPACC were evaluated using data from several different sources – an office building, a restaurant, and community college and university campuses, featuring constant- and variable-air-volume systems. Any evaluation using field data must contend with some inherent difficulties: reliance on sensor data to discern the true state of the system, the inability to report a “false positive” (an undetected fault), and ambiguity regarding what constitutes a fault. However, in this case consistent results across diverse testing environments gives a high level of confidence that the FDD tools will perform in an even greater variety of applications. Several faults were successfully detected and confirmed by building operations staff. Every site has been found to have at least one fault. Even though the sample size is small, these results appear to confirm the hypothesis that faults of the type that can be detected by these tools are common.

Recommendations

The following is recommended language for the Nonresidential ACM Manual.

2.5.3.12 Zone Terminal Controls

Description: ACMs shall be capable of modeling zone terminal controls with the

	following features: • *Variable air volume (VAV).* Zone loads are met by varying amount of supply air to the zone. • *Minimum box position.* The minimum supply air quantity of a VAV zone terminal control shall be set as a fixed amount per conditioned square foot or as a percent of peak supply air. • *(Re)heating Coil*. ACMs shall be capable of modeling heating coils (hot water or electric) in zone terminal units. ACMs may allow users to choose whether or not to model heating coils. • *Hydronic heating*. The ACM shall be able to model hydronic (hot water) zone heating. • *Electric Heating*. The ACM shall be able to model electric resistance zone heating. ACMs shall require the user to specify the above criteria for any zone terminal controls of the proposed system. The keyword MIN-CFM-RATIO shall be the minimum box position times 1.1 (not to exceed 1.0) to reflect imperfect operation of the VAV box, unless FDD controls are installed.
DOE-2 Keyword(s)	MIN-CFM-RATIO ZONE-HEAT-SOURCE
Input Type	Required
Tradeoffs	Yes
Modeling Rules for Proposed Design:	The reference method models any zone terminal controls for the proposed design as input by the user according to the plans and specifications for the building. All ACMs that explicitly model variable air volume systems shall not allow any minimum box position to be smaller than the air flow per square foot needed to meet the minimum occupancy ventilation rate.
Modeling Rules for Standard Design (New & Altered Existing):	For systems 3 and 4, the ACM shall model zone terminal controls for the standard design with the following features: Variable volume cooling and fixed volume heating Minimum box position set equal to the larger of: a) 30% of the peak supply volume for the zone; or b) The air flow needed to meet the minimum zone ventilation rate; or c) 0.4 cfm per square foot of conditioned floor area of the zone. Hydronic heating.

2.5.3.7 Air Economizers

Description:	The reference method is capable of simulating an economizer that: (1) modulates outside air and return rates to supply up to 100% of design supply air quantity as outside air; and, (2) modulates to a fixed position at which the minimum ventilation air is supplied when the economizer is not in operation. The reference method will

simulate at least two types of economizers and all ACMs shall receive input for these two types of economizers:

1. Integrated. The economizer is capable of providing partial cooling, even when additional mechanical cooling is required to meet the remainder of the cooling load. The economizer is shut off when outside air temperature or enthalpy is greater than a fixed setpoint.

2. Nonintegrated/fixed set point. This strategy allows only the economizer to operate below a fixed outside air temperature set point. Above that set point, only the compressor can provide cooling.

The default for MAX-OA-FRACTION shall be 0.9 to represent imperfect operation of the economizer.

DOE Keyword: ECONO-LIMIT
ECONO-LOCKOUT
ECONO-LOW-LIMIT
MAX-OA-FRACTION

Chapter 3 should be modified with the following language:

3.3.19 Air Handler and VAV Box Fault Detection & Diagnosis

Description: A nonresidential ACM may be approved with the optional capability of controls that allow for self detection and diagnostic of faults in air handlers and variable air volume boxes.

DOE Keyword: MIN-CFM-RATIO
MAX-OA-FRACTION

Input Type: Required

Tradeoffs: Yes

Modeling Rules for Proposed Design: ACMs shall model the optional feature of proposed design FDD controls as input by the user according to plans and specifications for the building. For systems with FDD controls the VAV box minimum flow ratio shall be the flow ratio as shown in plans and specifications. The economizer MAX-OA-FRACTION keyword shall be 1.0.

Modeling Rules for Standard Design (New): ACMs shall determine the standard design according to Table N2-10.

Modeling Rules for Standard Design (Existing Unchanged & Altered Existing): ACMs shall model the existing system as it occurs in the existing building. If the permit involves alterations, ACMs shall model the system before alterations.

Material for Compliance Manuals

It is recommended that only Chapter 8 of the Nonresidential Compliance Manual be changed to accommodate this measure since it will be dealt with as an Acceptance Requirement item. Additional information pertaining to the use of the FDD should be incorporated into the MECH-7-A form and simplifications made to the MECH-4-A.

Bibliography and Other Research

Information for this measure template has been taken from the PIER research project number 500-03-096-A3 report. This PIER report is available from the California Energy Commission's PIER group as an Adobe Acrobat file, and includes the detailed background and research related to this measure template proposal.

The hyperlink for this project is as follows:

http://www.energy.ca.gov/reports/2003-11-18_500-03-096-A3.PDF

The field study by the New Buildings Institute on rooftop unit performance can be found at:

http://www.newbuildings.org/downloads/NWPCC_SmallHVAC_Report_R3_.pdf