

Fault Detection and Diagnostics: Automated, Ongoing Commissioning Functionality for Large and Small HVAC Systems

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Synopsis

This paper highlights state-of-the-art fault detection and diagnostic (FDD) product developments being supported by the California Energy Commission's Public Interest Energy Research (PIER) program through the Advanced Automated Commercial HVAC Fault Detection and Diagnostics Commercialization Program. (www.archenergy.com/pier-fdd/) The goals of the FDD Program are to develop and demonstrate advanced fault detection and diagnostic methods and measurement equipment for cooling, heating, and ventilating systems; more advanced and fault-resistant HVAC equipment; and to work directly with manufacturers in order to implement improvements and innovations in commercially available equipment. The desired outcomes are improved indoor environmental quality, reduced energy use, reduced peak demand, and reduced pollution for the citizens of California. This paper will describe four of the five projects in the program. The fifth, an advanced outside air damper control technology (SpeciFlow™), is available commercially.

A variety of diagnostic approaches in development and in the market provide a new platform of equipment-level and system-level operating performance information that can effectively enhance building energy performance and operations/maintenance management. Larger scale deployment of FDD will help to transform building management services related to HVAC from the current "reactive" operations/maintenance approach toward a "performance reliability" operations standard.

About the Author

Mark Cherniack has been active in the sustainable energy profession for 30 years beginning with community energy planning in 1976. He served as a Conservation Analyst at the Northwest Power Planning Council during the first Power Plan and went on to open the Asia Office of the International Institute for Energy Conservation in Bangkok. He had further international experience through photovoltaic business development in India, Morocco, Sri Lanka and Viet Nam. Mark has worked in the global warming mitigation field, fuel cell technology and is the volunteer energy coordinator of the Mosier (OR) Community School for which he landed a 4.3kW PV tracking array in the school yard. He is senior program manager at New Buildings Institute responsible for Market Connections support for the CEC PIER FDD Program; on the

Market Connections Team for the CEC-PIER Hot/Dry Air Conditioner Project; and leading two projects related to the design of utility programs for small commercial rooftop HVAC O&M.

So Who's and What's at Fault?

Who?

Experience from the field continuously tells the same story for both large and small commercial HVAC systems: given the current state of HVAC operation and maintenance (O&M) services, approximately two thirds of all systems are operating at reduced performance levels ranging from trivial to dramatic, with performance degradation beginning anytime from the day the systems were designed/installed/placed in service, to the day replacement was required, as likely as not prematurely. The reasons for this are well documented and in fact are the powerful underlying drivers for the development and increasing growth in the building commissioning services industry. Deviations from the expected outcome of a new building design or retrofit project to the actual result run all the way from design intent to preventative maintenance, with the net effect of reducing equipment and system short and long term operating efficiency and performance, while wasting large amounts of energy and adding to greenhouse gas production.

The barriers to more energy efficient buildings are well known: building codes/standards rarely push the design envelope, risk averse building developers and designers stay with what they know, lease revenue pays the energy bills, for office buildings energy costs remain at 1% of total annual expenditures although this can represent 30% of building operating costs, lack of sufficient knowledge and experience with new approaches, fragmented design process, controls interoperability incompatibility, difficulty valuing maintenance savings, control techs not familiar enough with their own product capabilities, and much more.

With building owners and managers most often focused on HVAC functionality related to occupant comfort and safety, and not optimizing performance, the controls industry has naturally focused on providing automated building control systems (BAS) and energy management control systems (EMCS) that support this interest. For years, the industry has provided control systems that emphasized monitoring and basic ON/OFF fault detection functionality with limited alarms. Now, with the twin drivers of higher energy costs and growing interest in 'sustainable/green' building practice, various segments of the commercial building market including control vendors are actively looking for user-friendly methods to allow more efficient (total cost/performance) and effective (personnel) management and maintenance of the overall system. Increasingly the controls industry is moving to add enhanced FDD functionality to control systems.

What?

A high informative look at FDD and related controls approaches for optimizing energy performance in the commercial buildings sector "Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, the Energy Impact of Building Faults and Energy Saving Potential," Roth, K.W. *et.al.* TIAX/US DOE was completed in November 2005.

(www.tiaxllc.com/aboutus/pdfs/energy_imp_comm_bldg_cntrls_perf_diag_110105.pdf)

The study assessed four parts of control and diagnostic frameworks:

1. Evaluating the energy impacts of faults
2. Assessing the energy savings potential of control and diagnostic approaches
3. Analyzing the barriers to controls and diagnostics
4. Analyzing drivers for controls and diagnostics

The study uncovered more than 100 faults that occur in commercial building HVAC, lighting and water heating systems. Three key faults appear to account for about two-thirds of the energy impact of faults: HVAC left on when space is unoccupied, lights left on when space is unoccupied, and duct leakage. Fault-related energy waste in HVAC, lighting and large refrigeration systems runs 4%-20%. The major FDD and controls approaches appear to have simple payback periods ranging from 0-10 years, with many from 0-5 years. The authors assessed five FDD and four controls approaches to optimizing energy and environmental performance. They conclude from the available data, that advanced controls may have a greater impact on energy savings than diagnostics alone. However, the enhanced functionality of including diagnostics within the controls framework provides the most effective toolset for managing ongoing building energy performance. It is strongly recommended that every one interested in supporting the future of sustainable building performance take a look at this report to add to their understanding of the underlying value of 'intelligent' automated, control systems with high level diagnostic functionality.

FDD Non-Energy Benefits

There are also significant non-energy benefits of FDD that result from improved operations and maintenance (O&M) and from better control over the environmental conditions in the occupied spaces. Properly operating FDD tools should identify minor problems before they become major problems, thus extending the useful service life of equipment with the typically large capital equipment cost savings. Also, repairs can be scheduled when convenient, rather than causing undesirable downtime and costly overtime work. In some cases, identifying and repairing faults may make the difference between regulatory compliance and noncompliance, as well as liability questions. The FDD/controls study cited above identified the impact from productivity gains as the most potentially significant benefit from better controls and diagnostics. It notes that increasing office productivity by 2% has the same economic benefit as eliminating all building operations and energy expenditures. However, making this economic case is not straightforward.

Advances in technology sophistication along with reductions in cost have made the enhancement of control systems to encompass fault detection and diagnostic functionality throughout building and facilities justifiable.

PIER FDD Program Projects

The following are brief descriptions of four products being supported by the PIER program. Additional information can be found at www.archenergy.com/pier-fdd/

FDD Algorithms

Project Developer: National Institute for Standards and technology (NIST)

NIST staff have developed FDD algorithms suitable for embedding in AHU and VAV box controllers. There are two separate FDD algorithms: AHU performance assessment rules (APAR) evaluates knowledge-based rules to detect up to 28 fault conditions in single duct and constant volume AHU's with airside economizers. The VAV box performance assessment control charts (VPACC) implements a statistical quality control method to detect up to seven faults in most VAV box types. APAR and VPACC detect problems including mechanical failures such as stuck, broken, or leaking valves, dampers, or actuators; control problems related to failed or drifting sensors; poor feedback loop tuning or incorrect sequencing logic; degraded performance caused by heat exchanger fouling; design errors; or inappropriate operator intervention or lack thereof. The energy saving benefits of the FDD tools come from identifying and correcting those faults that cause increased energy consumption. A case study of the algorithms in use in a 1.4 million sq.ft. office building with 2 AHU's and 1200 VAV boxes which contains a complete list of the alarm faults can be found at the program's web site. The building's chief engineer is a strong proponent of the algorithms and the building's O&M service provider would recommend where possible, the use of the algorithms in all their service contracts.

Both sets of algorithms are intended to be written into manufacturer-specific control application programs along with the actual equipment control logic. Each AHU or VAV box is monitored by an algorithm running in its local controller. The results of the algorithms are reported to the building operator through the alarm and event handling features of the BAS/EMCS. The FDD algorithms not only monitor basic equipment function, they also detect and report on sub par performance. The algorithms are for use with BACnet™ compatible systems.

These algorithms are executed by the equipment controller as a component of the control logic, therefore they are not complete end-use products, but software enhancements for existing control application programs. This makes these new FDD tools accessible in the market through a potential variety of vendors. There are a number of advantages to embedding the FDD algorithm in the controller:

- It doesn't require additional third-party software that must be integrated with the control system.
- It scales better since it has local access to the data it needs, eliminating the need to communicate the data needed for FDD calculations via the BAS/EMCS network.
- The control program is written once and copied to each controller, so it doesn't have to be configured separately for each piece of equipment.

The algorithms automatically and continuously monitor the equipment with minimum human involvement and operating cost. Too often, commissioning is a one-time event. Embedded FDD

runs all the time reporting directly or remotely to the on duty building operator. FDD runs and essentially tests continuously in the background during normal operation. FDD can be a highly accurate tool to guide the commissioning agent to areas that may clearly need functional testing.

BAS/EMCS manufacturers provides a library of standard control application programs for use by application engineers. The deployment path for APAR and VPACC is to develop versions of the existing AHU and VAV box control application programs with interested controls vendors that have been modified to include logic to perform the appropriate FDD calculations in the vendor's controllers. In order to install the FDD tools at a specific site, the BAS dealer/representative would select application programs from the library close to the desired sequences of operation, identify the applicable threshold parameters from tables provided by the manufacturer, and configure alarm or event points for each AHU and VAV boxes.

The cost to the BAS manufacturer of providing this FDD functionality is relatively low and consists of the cost of modifying its standard control application programs and the cost of training its dealer/representatives to apply FDD. The revenue potential to the dealer is through offering customers value added services in the form of advanced control strategies. It may be expected that the FDD algorithms will be purchased as part of a larger project, either new construction or a controls system upgrade. Since the cost of FDD will be small, particularly relative to the cost of the entire project, it is unlikely that initial cost will be a key issue for the buyer.

One user of the algorithms, a building chief engineer who is described in the case study, has found that he can far more effectively direct preventative maintenance work to units that actually have problems, with the data he is getting back from the algorithms. Further, the building manager has integrated the algorithm outputs into the building's computerized maintenance management system that automatically generates work orders based on the alarms coming from the algorithms.

Based on the current operational success, relatively low implementation cost and full functionality of the NIST FDD algorithms in several buildings, it can be recommended that commissioning practitioners and related controls professionals look into this FDD approach for their clients. There is nothing quite like it in the market. Not all BAS/EMCS vendors' equipment can accommodate the algorithms due to proprietary access issues. Current controls industry participants supporting commercialization of the algorithms include Alerton Technologies, Automated Logic Corporation, Delta Controls and Tour Andover Controls.

Web-Enabled Fault Detection & Diagnostics

Project developer: Architectural Energy Corporation

This FDD tool is based on a version of the NIST APAR algorithms specifically designed to deal with dual-duct AHUs, chillers and cooling towers. The faults that are detected include conditions that violate schedules (*e.g.*, a fan running during unoccupied hours), sequences of operations (*e.g.*, a chilled water pump running when the chiller is not operating and interior

conditions are within set point range), detects a maintenance problem (e.g., a stuck damper), or reveals an energy-wasting trend (e.g., a slowly leaking valve).

The web-enabled automated diagnostics system will initially serve buildings with centralized cooling and heating plants with an existing BAS/EMCS. The FDD system will be a software application that analyzes trend data stored directly on the FDD platform's database. The BAS trend logs are not used. Additional sensors may be needed that can communicate directly to the diagnostic server through Modbus, LonTalk® and other protocols. These sensors will not have to be added directly to the EMCS. Its purpose will be to detect energy waste that is not typically identified by the existing BAS and to attempt to diagnose the source of the faults resulting in the energy waste. It will not provide event alarming or demand limiting control, which are functions commonly provided by the BAS, rather it will evaluate equipment operating performance. The diagnostic engine resides in a web-based environment where the data is analyzed and reported to the operator via a web site.

The integrated diagnostic engine developed is being developed as an independent component that will be available to BAS/EMCE applications providers who wish to incorporate it into their product offerings. Currently, the project developer has a non-exclusive development agreement with Tridium and the FDD tool is being built on the Tridium Niagara platform. To facilitate licensing this capability to third parties, data transfer interfaces will be developed using Extensible Markup Language (XML) over Hypertext Transfer Protocol (HTTP). XML over HTTP uses Uniform Resource Identifiers (URI's) with specific name/value pairs to invoke methods and processes within the web services framework. Once the URI is processed, a fully formatted XML document is returned as a response.

Service providers will have their own on-site data collection equipment. Data will be transferred to the service provider's servers at scheduled intervals. Next, the data will be transferred to the diagnostic web server for analysis. The results of this analysis are then returned to the service provider, and made available to the users via the World Wide Web in the form of reports or notifications. The diagnostics are currently in alpha phase testing at an athletic club with multiple AHU's, and district heat/water and steam service. Another test site involves a university campus library with a large dual duct system. Further development work is ongoing with drilldown capabilities, user interface, and adding plotting features.

Embedded Diagnostics for Rooftop Units

Project Developer: Field Diagnostic Services, Inc.

An embedded FDD tool for existing and new rooftop package units (5-50 tons) that uses wireless communications to report web-accessible diagnostic information to building owners and operators. Faults are reported in the refrigeration, air handling and controls systems. Fault reports document operational information such as trend plots, impact on occupant comfort, equipment safety, and energy costs, heating/cooling efficiency indices, runtime fractions, alarm history

The diagnostic hardware will be integrated into packaged units with or without economizer and demand-controlled ventilation controllers, and with single or dual stage compressors. There will be a technician interface at the unit for diagnostic information and immediate feedback on repair effectiveness. The user will have the option enable the fault alarms that are most relevant to their particular situation. Currently, there is nothing in the market that comes close to this level of operating performance information.

Table 1: Summary of Embedded Diagnostics Target Faults

Refrigeration Cycles	Air Handler	Controls
Poor condenser (high side) heat transfer	No economizer cooling at low outdoor air temperature	Continuous call for cooling or heating
Poor evaporator (low side) heat transfer	High outdoor air fraction when high outdoor air temperature	Simultaneous heating and cooling
Refrigerant flow restriction	Low outdoor air fraction during occupied period	Fan cycling during occupied period when should be continuous
Low refrigerant charge	DCV signal and low outdoor air fraction	Fan running continuously during unoccupied period
High refrigerant charge	Low mixed air temperature	Mechanical cooling at low outdoor air temperature when should be only economizer
Low compressor pumping efficiency	Low airside temperature difference during heating or cooling	Thermostat cooling demand but no cooling
Non-condensable gas in system	High airside temperature difference during heating or cooling	Thermostat heating demand but no heating
Sensor problem	Sensor problem	Unit short cycling; short off-time or runtime for compressor
		Extended runtime (long cycles)
		Sensor problem

For multiple units on a rooftop, each unit will contain a suite of temperature sensors to monitor its own operating performance. Data collected from each unit will be communicated wirelessly through radio frequency transmitters to a ‘master’ unit with an onboard Linux-based computer

with flashcard memory storage. At scheduled intervals, the master unit will communicate operating data from each unit wirelessly to a web-based user interface as shown in Figure 1.

Figure 1: Embedded Diagnostic User Interface

Unit	Comfort Alarm	Equipment Safety Alarm	Energy Savings Opportunity	Monitoring System Alarm	Efficiency Index	Potential Annual Savings	Expected Cost	Return on Investment
RTU-1	OK	2 alarms	1 alarms	OK	83	\$940	N/A	N/A
RTU-2	OK	2 alarms	1 alarms	OK	88	\$535	N/A	N/A
RTU-3	OK	1 alarms	1 alarms	OK	94	\$97	N/A	N/A
RTU-4	OK	OK	1 alarms	OK	N/A	N/A	N/A	N/A
RTU-5	OK	2 alarms	1 alarms	OK	79	\$301	N/A	N/A

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As shown above, in addition to alarm notification, the user interface provides operating efficiency benchmarks and several financial metrics to indicate the cost of energy inefficiency and potential financial return from taking action. The financial analysis information is developed through algorithms based on local energy costs and a known set of maintenance and repair options and related costs. The financial results are not precise, but are closely indicative.

Based on work by Dr. Jim Braun at Purdue University, the final commercial units will be using temperature sensors only for the diagnostics. Ongoing field tests continue to verify a 100% correlation between the temperature diagnostic algorithms and flow sensor measurements in the liquid discharge and suction lines, thereby eliminating the need for flow sensors in the final sensor suite. Currently, approximately 40 units are in various stages of field testing. Various commercialization channels for the product are being explored. It is likely that a product based on the sensor suite with web communications will be commercially offered sometime later in 2006.

Advanced Rooftop Unit

Project Manager: Architectural Energy Corporation

This FDD product is a specification for a cost effective, advanced packaged rooftop air conditioner unit (ARTU) based on the development of a laboratory prototype to evaluate the improvements. This product has important potential to impact state and national standards and codes based on its inherent design that promotes a performance maintenance approach. The new features should increase the likelihood that the energy savings potential of new HVAC equipment is achieved. The project's starting point was an initial set of definitions developed by the Consortium for Energy Efficiency in 2003, for an ARTU, but that effort had stalled due to

industry concerns about establishing specifications that were seen as potentially too prescriptive in nature. A number of parties in the energy efficiency community were interested in seeing the work continued.

This project will develop, test and demonstrate an ARTU prototype of 5 ton cooling capacity that addresses many of the energy and ventilation problems found in commercial building mechanical systems. Features of the ARTU will include improved outdoor air control, improved economizer reliability, diagnostics and troubleshooting capability, and fault-tolerant design. The end result will be a unit that operates according to prevailing ventilation standards, reduces energy use and requires less maintenance.

The ARTU project builds on an earlier PIER program that published the results of field studies in which two-thirds of more than 200 rooftop units, none of which were more than four years old, exhibited a number of problems with poor economizer operation, improper refrigerant charge, low air flow, high fan power and cycling fans, and other control issues. Such issues often go undetected by building owners and even service personnel. The program also produced performance guidance (“Integrated Design of Small Commercial HVAC Systems,” NBI/CEC 2004) for designers and operators on ways to improve the efficiency and operations of small package HVAC units. Many of these improvements could be integrated into a new “advanced” unit that would directly address performance and market impact objectives.

The project’s Technical Advisory Group including manufacturer representatives and consulting engineers with extensive rooftop unit working experience screened a list of FDD and equipment reliability/robustness characteristics. The group finalized a set of potential features by assessing currently available products and approaches that were available, typically in higher end units, but that had not been combined into a single unit. These features made the initial list for the laboratory test unit. The set of features to be tested combine the industry’s Tier 1 (minimum requirements) and 2 (Energy Star) feature sets with additional enhancements to improve energy efficiency. They also reviewed a third tier capability set by assessing more advanced features that were not quite ready for commercialization for one reason or another, but could be incorporated in a future ARTU. The unit’s FDD capabilities will include a subset of the FDD functionality being developed in the embedded diagnostic project noted above. ARTU features will address:

- Economizer Improvements
- Fan Improvements
- Unit Efficiency
- Refrigeration Cycle Improvements
- Fan Controls
- Refrigerant Control
- Thermostat Capability
- Sensors
- Installation & Check-out Capability
- Advanced Monitoring

- Advanced Diagnostics

A full description of the initial features set for the ARTU is available from the author. The ARTU unit will be engineered and tested in the first quarter of 2006. Based on the features finally selected, a benefit-cost analysis will be completed and the results widely disseminated throughout the manufacturing industry and among energy efficiency advocacy organizations.

Conclusions

A multitude of market interests and barriers must be addressed related to the issue of improving and maintaining reliable energy and operating performance in large and small commercial building HVAC systems. Deeply embedded social, cultural, engineering, design/construction attitudes and O&M practices appear to mitigate against making significant progress toward better performance. However, larger scale deployment of FDD and related ‘intelligent’ controls strategies should help to transform building management services related to HVAC from the current “reactive” maintenance approach toward a more “reliability-centered” approach. The availability of these tools will provide building operators with a new level of information to enhance operations management. FDD should also expand market interest in supporting the overall commissioning framework for new and existing buildings by providing embedded, automated equipment performance operating data on a continuous basis.

The market availability of more affordable FDD tools for built up systems and rooftop units will have an impact on the relationships between and among HVAC system designers, controls specifiers, building owners, building energy managers and third party energy service providers. The opportunity to more closely manage energy performance through near real-time operating performance data access, increased recordkeeping, and targeted maintenance will create additional transparency throughout the chain of relationships involved in building design and operations. Hopefully, this transparency will motivate increased accountability among the parties involved in the commercial buildings industry for increasing energy efficiency in buildings.