RTEM FAULT DETECTION AND DIAGNOSTICS (FDD)

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Introduction

The intersection of big data and building science is driving an explosion of interest in the development of software with advanced capabilities to optimize building operations. Accordingly, analytic software is one of the fastest growing areas for real-time energy management (RTEM). This category of technology, products, and services is commonly referred to as fault detection and diagnostics (FDD). Commercialized products ranging from enhanced alarm systems to advanced analytics are now widely available from traditional original equipment manufacturers (OEMs), controls vendors, engineering firms, and start-up ventures to meet every building application.

Increasingly, machine learning and artificial intelligence are being incorporated into FDD to perform data analytics, to process large quantities of data, and to continuously refine FDD algorithms to improve fault detection and diagnostic accuracy. This is perhaps one of the most exciting areas of progress, enabled by RTEM's cloud-based computing resources, rich datasets, and practically unlimited storage.

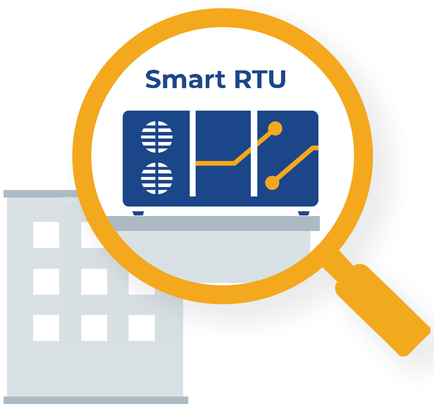
Traditional Adoption Barriers

Diligent building operators take pride in the excellence of their building operations and believe their staff are closely monitoring building equipment health. The potential contributions of FDD to upgrade operations are minimized. Consequently, they shift priorities to other budgeted measures and upgrades.

Operators of buildings with maintenance challenges are often aware of the problems, and the list of known repairs and upgrades can overwhelm the available manpower and budget. They may incorrectly conclude that adding FDD would only flag known problems or identify new faults of lower priority.

Real-world case studies published by the U.S. Department of Energy demonstrate that FDD can benefit building operations in both scenarios. The reality is that many operators of high-performance buildings are routinely incorporating the functionalities of RTEM with FDD into their daily workflow to keep their buildings continuously operating at a high level.

Equipment-Specific versus Building-Centric FDD



In the last decade, various rooftop units (RTUs), both packaged and split, have been manufactured with FDD functionality. The number of RTUs manufactured with economizers increased in response to revisions in ASHRAE 90.1. The comparatively high rate of dampers failing in economizer mode found during auditing, retro-commissioning, and the investigation of other failures led to the incorporation of economizer alarms and eventual development of automated fault detection in RTUs. Innovative RTEM vendors quickly recognized the need for a building-centric approach to FDD integrated with equipment-specific FDD. This leads to an upsurge in the development of products. Consequently, more and more FDD capabilities are being tightly integrated with RTEM, transforming a system that was used primarily for monitoring into a critical asset in the building operator's toolset.

Large buildings with central plants supplying many controllable zones tend to achieve lower cost per square foot ($\$/ft^2$) by deploying building-centric FDD, when evaluated on a $\$/ft^2$ basis.

Smaller buildings with few controllable zones, or buildings without central plants dominated by areas that are served individually by packaged or split units, tend to achieve lower $\$/ft^2$ by ordering FDD pre-integrated with the packaged unit.

Traditionally, building operators have relied on occupant complaints to report fault conditions. As the commercial real-estate industry strives to improve occupant comfort and to reduce occupant complaints, building operators are now looking for tools to detect problems proactively and to assist in diagnosing the root cause and fixing the problem before occupants lodge a complaint. As a result, FDD's ability to detect issues proactively has fueled its growth.

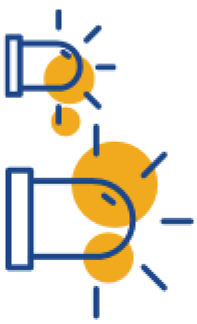
FDD versus BAS/BMS Alarms

Building operators have long relied on building automation systems (BAS) or building management systems (BMS) to detect failures using simple alarming functions.

The adoption of a BAS/BMS in commercial buildings usually brings a flood of alarms. In many BAS/BMS, every "point" can be associated with an alarm because threshold-based alarming in modern BAS/BMS is a low-cost option. There is an under-appreciated relationship where buildings with more advanced BAS/BMS are also the buildings with the most under-acknowledged alarms. At some properties, the problem has become so acute that the number of ongoing alarms has overwhelmed the ability of building staff to track down the issues. Consequently, some building staff have resorted to acknowledging or deactivating the alarms without bothering to troubleshoot the underlying root cause.

Although prudent alarm management helps, detecting a fault is usually insufficient for quick intervention. Helping the building operator to diagnose the root cause and to recover the faulty system rapidly is where FDD clearly is superior to BAS/BMS alarms.

Fault Detection Using BAS/BMS Alarms



Simple BAS/BMS alarming usually employs very basic threshold comparisons, where sensor readings or meter values exceed a predefined threshold. For example, large readings of a differential pressure sensor across the filter of an air handling unit (AHU) are used to detect and alarm filter clogging conditions. When properly configured and maintained, even simple alarming can be valuable in helping to diagnose problems, in concert with building staff training. Building operators also can be trained to watch the same alarm after initiating the ON command of AHU fans as an indicator of start-up failure and not as an indicator of inadequate airflow due to a clogged filter.

Beyond simple alarming, fault detection that combines multiple sensor readings showing a pattern over time usually requires the attention of an experienced troubleshooter, even with the availability of the advanced data visualization provided by many modern RTEM systems.

Advanced FDD is designed to address the conditions that would otherwise require experienced human intervention to detect and diagnose a fault condition.

Critical Role of Sensors and Meter Data

Sensors contribute to FDD capabilities by generating more data for the detection and diagnostic algorithms. Ideally, sensors embedded within a system (e.g., sensors in a chilled water system) are combined with independent meters that measure the overall time-interval energy consumption patterns of the system (e.g., electric meter for an electric chiller, meters measuring consumption of pumps and fans) to provide a comprehensive dataset for FDD.

Additional sensor and metering packages often are eliminated during the value engineering phase of a project. The rationale is that sensors and meters do not save energy when compared to a more direct conservation measure such as a variable-frequency drive (VFD) or when compared to a higher efficiency rated package. Sensors and meters play a crucial role by providing the high-quality data that allows FDD algorithms to perform.

Defining Faults

Faults that allow the building to meet all of its obligations (e.g., "setpoints") are insidious in that they often remain undiscovered, even when routine maintenance is performed. The underlying conditions may lead to the excessive wear and tear of a building's equipment, shortening the life of expensive capital assets, or creating disproportionately high energy spending compared to similar buildings.

A fault broadly is defined as equipment, a system or an entire plant that is not operating "as intended." A fault could also mean when the operation of the building's equipment, system or plant is "subpar." Under both scenarios, detecting and diagnosing faults can play a huge role in making sure the building is operating as efficiently as possible, and that it is uniquely optimized to meet its obligations.

Although the fundamental function of the FDD is to distinguish normal or proper operation from abnormal or improper operation, translating terms such as "as intended" and "subpar" into detectable events and actionable recommendations for corrective actions is often the core differentiator of the FDD implementation.

The next section provides an overview of FDD algorithms.

FDD Based on Physical Modeling

This approach is derived from the scientific underpinnings of building heating and cooling systems and involves principles of physics such as heat transfer, energy conservation, and fluid dynamics. Well-established engineering simplifications are incorporated to allow for the implementation under real-world software constraints. This method is best applied to well-understood systems, where an existing body of knowledge that defines the input-to-output relationships of building equipment enables the comparison of predicted with actual conditions to identify abnormalities. This approach is best used for steady-state conditions occurring within the equipment design conditions.

Usually, FDDs based on physical modeling are realized using one or more of the following approaches:

- Developing engineering calculations based on design conditions to define normal boundaries for comparison with actual conditions.
- Creating physical models to simulate equipment and system operation to differentiate between normal and abnormal conditions.
- Defining the rules that describe the boundaries of normal and abnormal conditions, usually based on the generally accepted best practices and empirical knowledge of experts.

FDD Based on Data Analytics

The FDD data analytic approach is primarily an empirical method. Data recorded under normal conditions is used as the baseline pattern to detect deviations. A large, comprehensive dataset capturing the inputs and outputs of the building equipment is essential. To narrow fault causes, a comprehensive dataset covering as many of the inputs and outputs as possible is necessary for diagnostic functions.

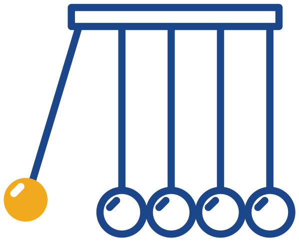
The data analytic approach is sometimes supplemented with physical modeling to speed up detection. Additionally, the physical principle approach may be used during the initial operation of the FDD algorithm until enough data is recorded to incorporate the unique building characteristics reflecting the differences in a building's design, occupation patterns, automation and control system programming, and local environmental conditions. Opportunities to unambiguously delineate normal data from abnormal data should be leveraged wherever possible, such as during the commissioning of a new installation or re-commissioning of existing equipment and plants.

Usually, data analytic FDDs are realized using one or more of the following approaches:

- Pattern recognition of datasets associated with normal conditions and abnormal conditions.
- Statistical processing of the dataset using techniques such as clustering, classification, estimation, and regression.

To minimize false alarms, both approaches (physical modeling and data analytics) use a threshold that defines the deviation from normal to abnormal conditions before triggering FDD event recording and reporting. Some FDD implementations also have a threshold for requiring a pre-set quantity of FDD events before triggering an alarm.

FDD Results with Large Impacts



FDD is capable of detecting and diagnosing large and small faults. Faults with potentially large impacts (employing wasteful sequences or failure of major systems over time) are shown below and may be difficult to identify because the building would likely operate at set points.

Zone Conditioning Faults:

- Zone being conditioned to meet lease obligations much too early before the start of the occupied period.
- Zone being conditioned to meet lease obligations for much too long after the occupied period has ended.

Air Handling Unit Faults:

- Not economizing to take advantage of free heating or cooling.
- Too much outside air being introduced that requires mechanical conditioning.
- Simultaneous heating and cooling.
- Fan operating during the unoccupied period.
- Heating or cooling operating during the unoccupied period.
- Excessive valve cycling.
- Valve in by-pass mode.
- Valve leaking.
- Ductwork leaking.

Chiller Central Plant Faults:

- Prolonged period of operating under low Delta-T conditions.
- Chilled water setpoint too high or too low.
- Inefficient staging of chillers.
- Chiller constantly operating at low load.
- Continuous degradation of evaporator heat exchange performance (indicating fouling).
- Continuous degradation of condenser heat exchange performance (indicating fouling).
- Continuous degradation of chiller efficiency.

Whole Building Faults:

- The building is operating at higher energy consumption relative to the comparable baseline condition (with similar weather conditions and occupation levels).
- The building demand is in danger of setting a new peak.

Without RTEM and FDD, many faults remain undiscovered or undiagnosed for years, until a building undergoes comprehensive re-commissioning. These faults could have large energy impacts that account for between 4% and 20% of the annual energy consumption for the affected end uses[1].

Planning for FDD Deployment

The efficacy of FDD depends on the algorithms having access to a large quantity of high-quality data to distinguish normal from abnormal operations. By its nature, thorough testing of FDD across all its various permutations is often impractical under real-world deployments. Nonetheless, a testing period should be included during the planning phase. During the testing period, purposely introduced faults such as the ones that are likely to occur are often very useful to train the building staff to have confidence in the FDD. For complex deployments with hundreds and thousands of data points, it is critical to include an extended commissioning phase to uncover various installation and deployment issues. Thresholds also need to be fine tuned during the commissioning phase and alarming/reporting functions integrated with the building operator workflows for corrective actions or to escalate priorities.

Building operators should expect the discovery of hidden existing issues within the sensors and metering devices during the FDD deployment. Repairing or replacing the faulty sensors and meters during a structured testing phase avoids the loss of confidence that the FDD algorithms are not reliable. The

[1]Energy Impact of Commercial Building Controls and Performance Diagnostics, Final Report, U.S. Department of Energy Building Technology Program, November 2005

testing phase also allows the “shake out” of incorrectly configured or labeled data sources in the existing control systems or data historian system long left unaddressed.

Similar to the commissioning of any other building system, the importance of starting a new deployment with a clean slate is often one of the most underappreciated best practices in the industry.