USING ENERGY MANAGEMENT CONTROL SYSTEMS FOR HVAC OPERATIONAL DIAGNOSTICS

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ABSTRACT

The power and flexibility in building energy management systems (EMS) provide building operators, system consultants and technicians with a useful tool for assessing building equipment and system operation. This paper describes specific methods and techniques for using the EMS to verify proper equipment operation and to diagnose operational deficiencies. Two primary methods are discussed: monitoring using trend logs to observe performance over time, and functional spot testing using the EMS. Discussion covers what EMS points to trend, how to efficiently set up trends, how to obtain data and what to look for in analyzing the data for a variety of typical equipment types. Examples and illustrations are provided.

BACKGROUND

Operational diagnostics are testing procedures that provide information to a technician on how well the component or system is functioning relative to the original operating parameters and acceptable practice. Diagnostics can be used to investigate control loops, verify their operation, and ensure that efficient equipment operation continues as desired. This paper will describe two primary methods for using an energy management control system (EMS) for diagnostics: Trending Performance Over Time and Functional Spot Testing.

CALIBRATION

Before an EMS can confidently be used for diagnostics, it is necessary to calibrate all sensors and actuators in the system to be trended or tested. This provides reliability to the values and conditions reported by the trends or EMS screen readouts. Summarily, calibrations for sensors consist of a comparison between the EMS value readout and a hand-held, recently calibrated, instrument reading placed near the EMS sensor. The EMS readout is then adjusted to match the hand-held reading to within the accuracy of the EMS sensor. This is ideally done over the range expected to be experienced by the sensor. Similarly, actuators, dampers, and valves must have their closed, full open, and intermediate positions reported in the EMS actually verified by visual inspection (PECI 1997).

TRENDING

Trend data is a collection of data readings taken at discreet intervals by the EMS and can be an excellent tool for diagnostics. Many current control systems have adequate trend logging features (Heinemeier 1992; Liu 1994). Others may require software upgrades to efficiently construct trend logs. Some systems are limited by the number of points they can trend simultaneously, by capacity issues, or by sampling speed limitations. Other systems do not allow the output to be saved in a file format readily useable in commercial graphing spreadsheets. Often, trending setup and downloading details are poorly described in controls operations and maintenance (O&M) manuals (Koran 1994). Prior to beginning a trending project, contact the controls vendor for assistance.

Planning and Setting Up Trends

A trending plan consists of the points list to be trended, the value type to be trended (value stream or change of value, explained below), the sampling rate, the trend group with which each point will be analyzed, the purpose of the trend, and the visual method of analysis to be used.

What to Trend. Decisions on what to trend could be based on the following priorities:

1. Systems or areas with *known* comfort or operational problems,
2. Systems *suspected* of faulty operation,
3. Systems at high risk for problems, such as economizers, variable speed drives, mixing valves, etc.,
4. Systems that consume large amounts of energy, such as chiller systems, air handler units and lighting,
5. Systems that have recently been repaired or retrofitted and for which functional verification is desired.

Review control drawings, the points list, and the sequences of operations. This documentation will provide a view of what points are available to trend and the sequences that may need verification. Table 1 provides a small set of possible trends, including a recommended sampling rate. The table also provides brief guidance on analyzing the trend and analogous functional spot tests for checking out the same components (PECI 1997).

Trend Types

There are two trend types: value stream and change of value (COV). The value stream takes an instantaneous reading of the point value (temperature, pressure, etc.) at each sampling interval. A COV trend does not record a value until the point value has changed by a pre-specified amount. COV trends use less cabinet memory (if COV specified change is not too small) and COV are easy to follow on columnar printouts. COV data has irregular time intervals and requires converting the text to numerical values to graph.

Sampling Rates

The proper sampling rate depends on the purpose of the trend, the type of equipment being monitored, and the memory limitations of the EMS. The system has limits on how many points it can sample instantaneously. Trending a large number of points simultaneously (e.g. 100) can lead to discontinuous data and problematic analysis.

If the purpose of the trend is to investigate possible hunting of actuators or short cycling of equipment, the sampling rate should be ideally about 2 minutes. Some hunting can be detected using wider intervals up to 30 minutes, but the intensity of the hunting or cycling may be masked. Figure 1 illustrates this issue by comparing discharge air temperature and setpoint from a rooftop air conditioner during the same time frame sampled at three different rates (2, 16 and 32 minutes). Between every two peaks of each overshoot cycle on the 32-minute sample, there are really two more cycles, as shown in the two-minute sample. Hunting and short cycling can also be detected by using a COV trend of the equipment status, setpoint or parameter value. In such cases it is important to set the incremental change when the EMS will log a new value small enough so as to not lose resolution and mask some of the cycling.

For trending parameters whose significant changes are slow, such as space or outside air temperatures, a 15- to 30-minute sampling rate is generally adequate. Recording the average of many readings over the wider sample window minimizes the potential for recording erratic readings. Often, however, points must be sampled at a faster rate to be consistent with other points requiring a smaller time step.

Grouping Parameters

For larger trending projects of more than six or eight points, assign each point to a group for reference, representing points to be analyzed together. All points within this group should ideally have the same sampling rate.

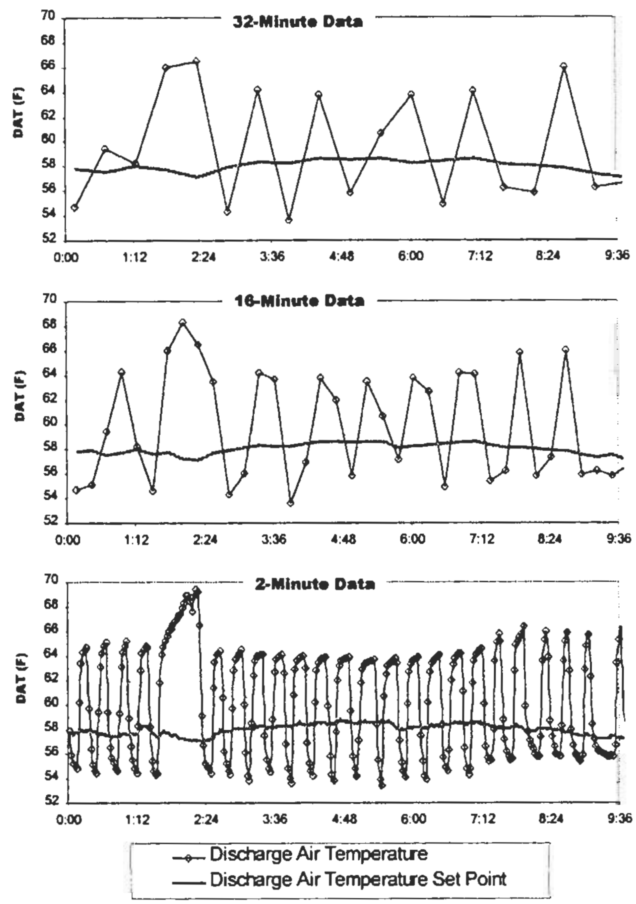

Figure 1. Effect of Sample Rate on Trend Graph Resolution

Large Trends

What is considered large is relative to the capabilities of the EMS. "Largeness" depends on how many points will be monitored, the sampling frequency, and the duration of the trend. For a new system in a 200,000 square foot building, for example, trending over 75 points at six minute intervals for one week may be considered large, but manageable, while old systems may not be able to handle even a quarter of that.

Many EMS trends are generated and data initially stored in the control cabinet from which their points are controlled. For large data sets when cabinet memory is at its limit, the points of one trend may have to have a larger time step (interval) than points in another trend from the same cabinet to reduce the total number of stored values. In large trends, using as many COV trend types as possible is recommended, as the memory and resources they require are often much less. Another solution is to add memory to the control cabinet.

Memory capacity is not the only problem with large trends. Computer resources for performing all the tasks of the EMS are also strained by large trends. The result can be skipped polling, missing data points and skipped downloads. This is especially a problem for an EMS that initiates and executes trends from the central computer CPU rather than from the distributed control cabinet CPUs. Another solution for large trend projects is to divide the trending into two phases, e.g., run a few trend groups one week and then a few other groups the following week.

Starting Times

Some energy management systems can schedule start and stop times of trends, while in other EMS software, the trending begins as soon as the trend is defined. When data will be viewed in columnar format or via EMS software graphics only, starting different trends at precisely the same time is not critical. For data to be graphed in commercial spreadsheets, identical start times and time steps may be required important. However, with a little effort, different start times and time steps can be accommodated in newer spreadsheets.

Maximums and Minimums

Many energy management systems can trend the maximum or minimum of a point over a given time interval. This feature can be used to identify operational problems. Possible setups are to record the minimum and maximum values of a space temperature sensor or fan discharge pressure over every 30 minutes. Extremes outside acceptable operating ranges indicate problems.

Totalization and Counting

Many energy management systems have the ability to sum up the number of hours of operation for a piece of equipment. This can be valuable for preventative maintenance planning. In addition, the EMS can count how many times the equipment has turned on and off during a given period to determine cycling rates. Totalization can also be used to determine the energy use over time in kWh by totaling kW pulses.

Example Trend Graphs

The following figures provide actual examples for some of the above trends. Figure 2 illustrates how chiller loading can be tracked with outside air temperature (OSAT). As expected, as the OSAT increases, so does the chiller load. Note how the two Y axes and ranges improve resolution.

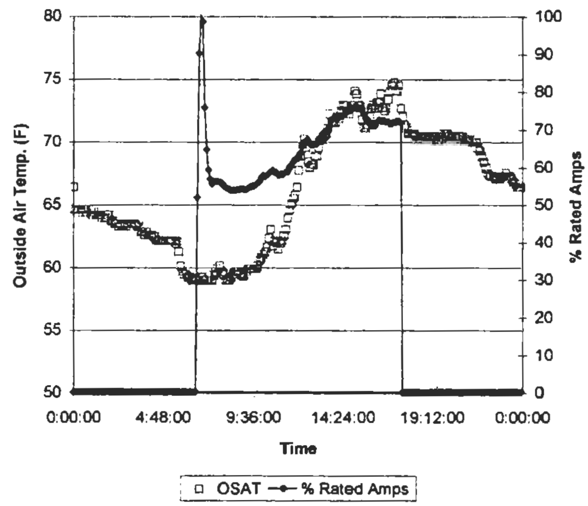

Figure 2. Chiller Loading vs. OSAT

Figure 3, in time series, compares the OSAT with the heating water supply temperature (HWST). This system had a reset and as expected, as the OSAT increases, the HWST decreases. However, it is difficult to determine if the system is being reset properly. Figure 4 plots the same data, by plotting one parameter against another, rather than against time. From this graph it can be easily determined that the reset is working, but not to the specified schedule—a programming problem.

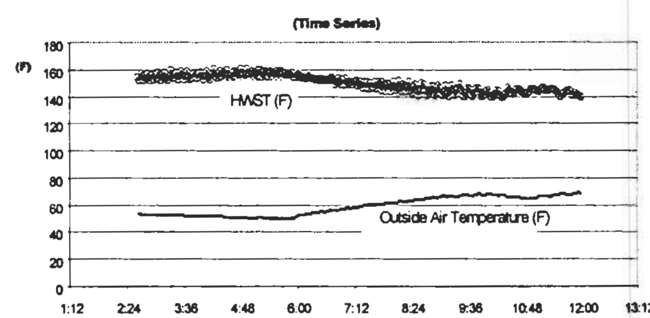

Figure 3. Investigation of Reset Schedule via Time Series Plot

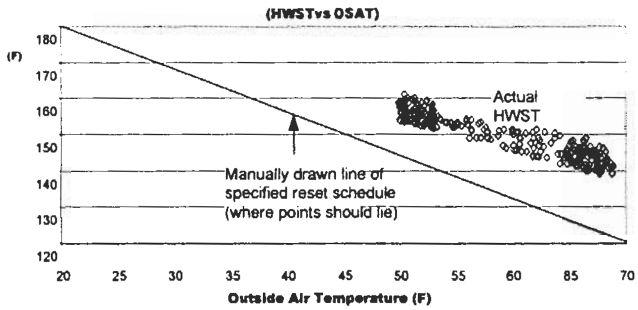

Figure 4. Investigation of Reset Schedule via Plotting One Parameter Against Another

The data in Figure 5 shows, relative to the chiller, the entering condenser water temperature (ECDWT), the leaving condenser water temperature (LCDWT), the ECDW setpoint (SP) and the bypass valve position (normally closed NC) in volts. The graph shows the LCDWT to be lower than the ECDWT!! This is impossible. The cause was that the sensors had been reversed at installation.

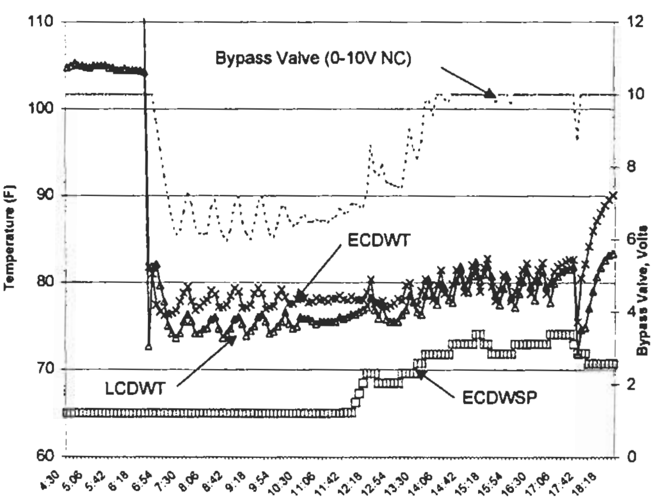

Figure 5. Malfunctioning Chiller and Cooling Tower

Figure 6 evaluates the operation of the face and bypass dampers and cooling coil valve (CCV) operation (0-10V, NC). Close inspection indicates that there is leak-by past the bypass damper, since the air off the coil (CCT) is in the low 50's, the bypass damper is closed all day, the supply air temperature (SAT) cannot always meet its 62F fixed setpoint and the SAT follows the trend of the entering OSAT.

The whole building demand data of Figure 7 shows a large spike on one day and no spike on the next day. Investigation determined that the large spike was common on most days, but was unnecessary, being caused by resistance heaters all coming on at once.

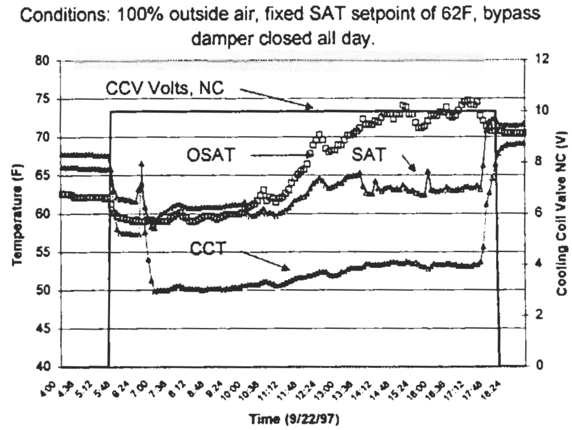

Figure 6. Leak-By in Face and Bypass Damper

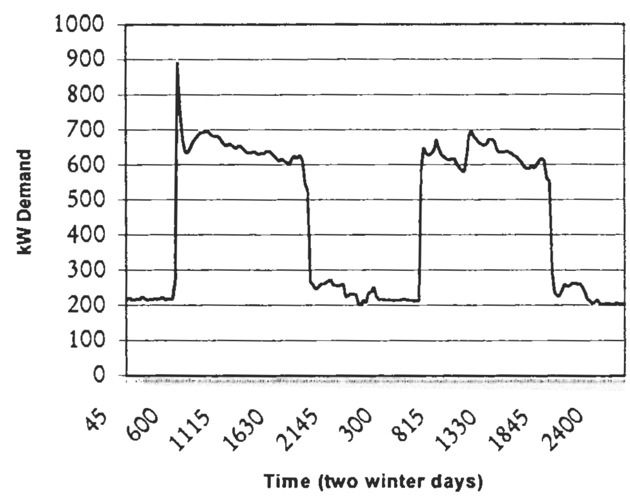

Figure 7. Demand Spikes at Start-Up

<u>Downloading Trend Data</u>

A full understanding of the different ways that the EMS stores and handles trend data will help prevent lost data. Generally, asking for a contiguous set of data is preferred, rather than a "report" consisting of pages of 66 lines of data separated by page headers, since clean-up or sorting is then required before graphing can be accomplished. It must be known whether the data will automatically download to the EMS hard drive when full, whether the EMS must be specifically instructed when to download, or whether manual downloading is required. If the system does not automatically download, find out from the vendor whether a software module to do so is available, and what rule of thumb is used to calculate the storage needed for large trends. Ask how much storage is available in each cabinet, and understand how to determine when a cabinet is at its memory limit. This will allow determination of the frequency of pre-assigned or manual downloads. Some cabinets have a first in, first out trend storage and dumping feature.

NON-TRENDING DATA SOURCES

Most EMS have features that provide trend-like data almost automatically. These features provide a valuable resource for diagnosing system functions.

Auto-Diagnostics

Auto-diagnostics are not traditional trend logs, though they consist of stored data similar to trends. Auto-diagnostic functions of some equipment controllers report through the EMS. These can be valuable for predicting problems and for determining causes of malfunctions. For example, a particular VAV controller automatically calculates the ratio of damper actuator runtime to total controller runtime. Ratios over 5% indicate possible problems. The controller also calculates the moving average flow error of the terminal unit (TU). If this is greater than 10% of the maximum box CFM rating, there may be a flow sensor or control loop malfunction. The moving average space temperature deviation is also tracked and can immediately detect when there is a problem. This is all done continuously and automatically, without any setup of trends.

History Logs

Many energy management systems will continually trend a point for the last 24 hours by simply selecting this option in a "point history" menu. At any time, the point history can be called up and viewed graphically on screen.

Scheduled and Process Start and Stop Reports

Similar to an ON/OFF COV trend, some systems automatically generate reports called Scheduled and Process Start and Stop reports. The information for these reports is continuously generated in the background. All it takes is a call for the report by system (e.g., AHU-3) which then provides the date, time, event (command on or off), status of the unit (normal, override) and the reason for the change in status (schedule, a process, manual command, etc.) for the last few days.

Alarms and Relational Checks

Alarm functions can be used to alert staff when parameter values are outside certain ranges, thereby indicating possible malfunctions. These alarms or reports can be the result of a comparison of parameter values providing a relational check of equipment operation (Meyers, 1996). For example, alarms could be set when the entering condenser water temperature is greater than the setpoint by more than 3F, indicating valve or pump problems. Such alarm functions must be limited to periods when the equipment is running, etc. to eliminate nuisance alarms.

DISPLAY OF TREND DATA

There are five ways that data can be viewed by the analyst (depending on the system):

- Columnar display on EMS computer screen
- Columnar hard copy printout
- Real time graphical display on the EMS computer screen
- Graphical display in spreadsheets (historical data)
- Real time graphical display in spreadsheets

Columnar Display on EMS Computer Screen

This view consists of columns of data with time in the left-most column and columns of different trended points in adjacent columns. This is useful where analysis will be quick and returning to the data again later is not likely. This is a good way to view standing history logs when troubleshooting new problems without having to set up and analyze a special trend log or graph. This format provides accurate values, but is not near as easy as graphs for following trends and detecting subtle changes and correlation among parameters.

Columnar Hard Copy Printout

This view is a print out of the columnar data viewed on screen. It has the advantage of being permanent and can be referred to again as needed.

Real Time Graphical Display on the EMS Screen

Some energy management systems have the capability to view current trend data (including multiple points) on screen as a graph. After a preset time period (a few seconds or minutes), the screen is updated with any new data from the trends. Older data to the left of the screen scrolls off, but can still be seen by using the screen control arrows. The scales or ranges for each point can be assigned, but this screen viewing method on many EMS is crude, may not have Y axis scales visible, and has low resolution. Nonetheless, this method is very useful for analyzing current issues where the problems may be identified without need for high resolution.

Graphical Display in Spreadsheets (historical data)

The most versatile method for viewing and analyzing trend data is to import the data into a commercial spreadsheet program and use its graphing capabilities. It takes time to do this, and other methods of viewing the data should generally be used first if they will provide adequate results. However, using a spreadsheet is preferred when performing troubleshooting on a complex problem, when fine-tuning control loops where good resolution is required, or when a printed graph for analysis and presentation to others is needed. Spreadsheets provide clear graphs with full resolution and have scaling and labeling features allowing for accurate analysis. Other commercial software for just viewing monitored data are also becoming available and will further simplify the graphing process (Kissock, *Emodel* 1993, Sparks, *Animate* 1995, Sparks, *Look-3D* 1995).

Using Spreadsheets

Converting to Spreadsheet Format. Data stored by the EMS usually needs to be converted to another file format before it is compatible with spreadsheet software. Some systems require the data to be converted to spreadsheet format after the data has been gathered, while others allow the user to declare the format of the downloaded data beforehand. Data storage in a text file (.txt) with comma or tab separators between columns works well, but requires a conversion when importing to a spreadsheet. The preferred format is .CSV, which requires no conversion by the spreadsheet. Make sure the layout of the stored data has time down the left column and as many columns of parameter values to the right as possible. Do not allow data in large trends to have a set of new parameters start at the end of the columns of the preceding data set. Before starting an important trend, experiment on a small trend to be sure the conversion process works.

Opening Data Files. When opening a data file, if it is not a spreadsheet or a .CSV file, the data must be parsed or delimited (divided) into columns. Newer spreadsheet software will automatically provide a systematic process to do this.

Setting Up Graphs. Consider the following pointers when using spreadsheets: Combine multiple download files into one spreadsheet to graph desired parameters together. Convert COV text to numeric values. Remove any extraneous text in the data (e.g., sort data to push all page break text to bottom, etc.). For parameters plotted against time on the X-axis (time-series), use an X-Y or line graph type. For plotting one parameter against another, use the scatter plot type as illustrated in Figure 4 and in Meyers 1996.

Adjust the scaling on the Y-axis to obtain high resolution by setting the maximums and minimums so the data at some point reaches close to the top and bottom of the graph. Truncate the X-axis to provide a "zoomed in" view of the data, as necessary. When graphing two or more variables that have a wide range in values from each other, assign the variables with similar maximum and minimum values to the right or second Y-axis. This greatly enhances the resolution of the data. However, if not carefully viewed, it can mislead the viewer as to the magnitude of the events. See Figures 2, 5 and 6.

Real Time Graphical Display In Spreadsheets

Some energy management systems have the capability to set up trend logs and then transfer the data live to a spreadsheet program using dynamic data exchange (DDE) software. This allows the user to view trend data in real time. It has the advantages of real time EMS computer screen display mentioned above plus the versatility of a spreadsheet. The value of this type of setup is that once the trend and DDE are set up, the user can at any time during the trend (or after) open the spreadsheet and view (both graphically and in columnar form) the historical and current state of the trended variables.

Remote Sites

Technology is now available that allows both real-time and historical data to be transmitted over the Internet to a remote site where spreadsheet or other specialized application analysts can observe and diagnose system operation.

ANALYZING DATA

Data analysis begins with a decision on how to display the data. For initial analysis, start by viewing the real-time on-screen graph. If more resolution is needed or if a control loop is being tuned, analyze using spreadsheet graphs. If the output is limited to columnar viewing, the analysis method is limited to printing out the data and paging through it to diagnose the system. Also, for non-COV data, consider constructing scatter plots (plotting one variable against another rather than against time. See Figure 4.). Add new points to trends as clues to the malfunction are uncovered. During analysis, consider the following four primary reasons for most malfunctions of equipment:

1. Sensors or actuators out of calibration
2. Hardware malfunction

3. Faulty sequences of operation (programming)
4. Improper set points

For each component, consider if each of the above reasons may apply. If so, monitor or test the function to verify proper operation. Also, think about the stream of values for each point: what should be happening to the point values at different times of the day in comparison to the outside air temperature (for example) or to other points being trended? Review the sequence of operations for the system being analyzed and recreate what is happening in the trends compared to what the written sequences say. For example, when examining a heating water reset sequence, observe both variables in the strategy, e.g., outside air temperature (OSAT) and heating water supply temperature (HWST). Trend not only the value, but also the setpoint itself. Observe that when the OSAT raises, the HWST drops. Remember that most control loops have bias or deadbands as well as time delays to prevent cycling or to save energy. Not understanding exactly what these parameters are can lead to erroneous conclusions.

Be aware that an ON status simply indicates that the software has calculated that the device should be ON; not that there is feedback proving an ON condition. If available, trend the feedback point, as well. Likewise, trending a valve position *command* is only that—a command. It does not guarantee that the valve is actually at that position, unless recently calibrated.

When analyzing trends, be familiar with any atypical activities occurring in the building. Special tenant events during occupied or unoccupied hours or service contractor and other facility staff activities such as taking equipment out of auto or normal mode for servicing can cause trend data to be very difficult to interpret if not accounted for.

Documenting and Reporting the Trending Analysis

During the analysis, whether graphical or columnar, write notes, observations, and conclusions on the trends themselves to aid in future review of the problem. Some problems can be identified by the analyst without "slick" graphs, however, printing a clear graph may be the most efficient and effective way to communicate the findings to others.

FUNCTIONAL SPOT TESTING

Besides using the EMS for trend-logging data over time, the EMS can be a valuable tool in troubleshooting system problems and enhancing operation through immediate observation of point values on the EMS screen. This is termed functionally spot testing systems. The EMS can make the testing quick and reliable and requires fewer staff to execute than tests that rely only on hand-held instruments and visual verification. As with trending, point calibration is a prerequisite to functional spot testing.

Functional spot testing with EMS utilizes on-screen control system readouts to verify performance of equipment. The EMS is used to change a setpoint or parameter that will cause a reaction in the system of interest. The response of the system is then immediately observed on the EMS screen. For example, to see if the heating valve position is working properly on a VAV box, the zone temperature set point could be raised 10°F and the response of the heating valve immediately observed. Like trending, calibration of all affected sensors and actuators is required before functional spot testing can rely on the EMS readouts.

Functional spot testing differs from monitoring or trending in that trending generally looks at the performance of systems over time—historically, after the event occurred. In a trend, the operator must "piece" together what happened to cause a given response in the system, whereas in functional spot testing the operator overtly initiates the action and immediately observes the response. Also, trending typically cannot alone record the extremes of system operation, but is limited to recording what happened under normal external conditions. With functional spot testing, the system can easily be taken to design conditions or tested under any other desired state by simulating a condition. For example, to test an economizer damper, during the cooling mode the outside air temperature (or enthalpy if appropriate) could be overwritten to be 50°F, simulating a condition appropriate for economizing using the EMS. The damper response is then observed in the EMS (or visually if damper position is not monitored). Functional spot testing also allows for checking of components that may not be observable in the EMS, e.g., damper position, boiler stage, etc.

Simulating desired conditions may be accomplished by changing set points, overwriting analog input values, jumpering contacts, closing power disconnects, changing schedules, and false loading equipment. Be sure to return all conditions to normal after testing is complete.

When functionally spot testing, check the system response just above and below the deadband of the breakpoint. For instance, in the above economizer example, if the changeover setpoint was 65°F with a 2°F deadband (+/- 1°F), then overwriting the OSAT to be 50°F may verify the economizer works, but not that it works *properly*. To do that, the OSAT should be overwritten to 62°F and see that the damper opens; then overwrite the OSAT to 68°F and see that it closes. Alternately, change the change-over setpoint rather than overwriting the OSAT.

Functional Spot Testing / Trending Combination

Functional spot testing and trending can be combined when necessary. The trend or point history log is started and then conditions are altered or simulated like in a functional spot test, but instead of immediately viewing the response, it is recorded in the trend data and viewed later. This is useful for observing the response to a parameter or condition change over time. For example, if it was desired to know if the chiller demand limiter was functioning properly, but the load on the chiller was not currently high enough, lower the EMS demand limit set point for a few days and trend the chiller demand limiting parameter (current or kW) during that period.

What to Functionally Spot Test

The previous section, *What to Trend*, provides rationale that also applies when determining what and when to functionally spot test. Table 1 provides a list of possible systems and components to functionally spot test to identify unknown problems or to illuminate suspected ones.

Functional Spot Test Documentation

Small tests for diagnostic purposes can be conceived and executed without prior written planning, but these should still be documented during testing. Notes should be kept on the conditions of the test, what was done to initiate a response and what the response was. Longer tests or checkout warrant a written procedures.

Table 1. Sample Trends and Functional Spot Tests (3 pages)

Issue or Equipment	Points to Trend and *Sampling Interval*	Analysis Summary	Functional Spot Tests
Identify unnecessary equipment operation (chillers, pumps, air handlers, exhaust fans, lights, etc.)	Change of value (COV), another indicator or an ON condition Time-series also works well. *(COV or time-series 15 min.)*	Make sure HVAC is not unnecessarily ON outside of occupancy periods. Verify that lighting ON-times appropriately match HVAC schedules.	Change schedule to sweep or shut OFF lights now and observe results. Verify all lights in all parts of the building.
Chiller start	Turn-ON parameter (cooling coil valve position, OSAT, etc.) *(15 min.)*	Make sure chiller is not on unless the desired parameters requirement are met.	Use EMS to initiate a call for the turn-ON parameter and observe chiller start.
Chiller loading	Chiller current or kW, OSAT *(15 min.)*	Make sure the chiller current draw or kW goes up with OSAT. Make sure the chiller is not ON below OSAT < 55F without good reason. See Figure 2.	Use trend logs instead.
Chilled water reset (heating water is similar)	Chilled water supply temperature, CWST reset parameter (OSAT, valve position, etc.) *(15 min.)*	Graph CHWST against OSAT or valve position and compare to reset schedule, or analyze columnar data, similarly. See Figures 3 and 4 for heating water which is similar.	Use EMS to cause reset parameter to change, observe CHWST and setpoint change.
Cooling tower operation (fans, mixing valve and entering condenser reset)	Fan stage, valve position, tower sump, entering and leaving condenser water temperature, reset parameter (OSA WB, DB), fan stage parameter. *(5 min.)*	Compare the fan staging with the schedule, compare the entering condenser temperature with its schedule and compare valve operation to expected (closed when entering condenser water ≤ setpoint). See Figure 5 and Liu 1997.	Use EMS to initiate a call for cooling from no load to full load. Observe the actions of all parameters listed in the Points to Trend cell and observe per analysis cell (adjacent).

Table 1. Sample Trends and Functional Spot Tests (3 pages)

Issue or Equipment	Points to Trend and *Sampling Interval*	Analysis Summary	Functional Spot Tests
Chiller efficiency	Primary chilled water and condenser flow (or use values in TAB or start-up report), entering and leaving chilled water temp. and chiller kW (or current, if no kW). For reference, also trend entering and leaving condenser water temperatures. *(15 min. for 2 weeks)*	Calculate the kW/ton of cooling for all points and add this column to the data in a spreadsheet. Plot the kW/ton (Y-axis) against the chiller % full load. Save this graph as a benchmark. During similar weather the next season, repeat the trend and graph and see if the kW/ton generally remains the same or is degrading (possibly indicating fouling). Compare, by visual interpolation, to manufacturer's kW/ton data. Tons = 0.0417 x gpm x (CHWRT – CHWST). kW = Volts x Amps x 1.732 x power factor/1000, though direct kW meter value preferred. Get PF from start-up report or spot-check it (PF = W / (V x A x 1.732)).	Use trend logs instead.
Variable speed drives, VSD, (chilled or heating water pump, fans, etc.)	Rpm or Hertz, speed controlling parameter value and setpoint (pressure, temp., etc.), related load parameters (OSAT, chilled water temp., supply air temp., etc.)	Verify that speed modulates with load and the controlling setpoint is maintained without hunting. Verify that when the cooling or heating load is at its minimum, the rpm is as low as the motor can safely handle without overheating or cavitating. If it won't go below 30% speed, justify why. To verify how low is safe, perform a Hz vs. amps test, by manually incrementally lowering the motor speed and recording the amps. Amps will lower with speed, but when amps begin to increase, the lower limit is identified.	Use functional spot test for determining lower limit for VSD. Use EMS (change setpoints or overwrite conditions) to cause a change in cooling or applicable load. Observe the drive ramp up and down and go below 30% speed when minimum load, etc.
Simultaneous heating and cooling	Heating element enable or valve position, supply temp., cooling coil valve position *(2 min.)*	Make sure that when the cooling coil valve is open, the heating coil valve is closed.	Use EMS to change to cooling and heating load call and analyze per adjacent cell.
Air-side economizer functions	OSAT, MAT, RAT, SAT, OSA damper position (because many EMS do not monitor damper position, and using a temperature difference to calculate %OSA is inaccurate when OSAT is close to RAT, consider a functional spot test) *(2-5 min.)*	In spreadsheet, estimate damper position from % OSA, using: %OSA = (RAT – MAT) / (RAT – OSAT). This is inaccurate when RAT~OSAT. Are outside air dampers fully closed during warm-up? Do economizer dampers open, and return air dampers close, to maintain discharge air setpoint right at the economizer change-over point (enthalpy or dry bulb)? Is the enthalpy or dry bulb sensor calibrated? Does the change-over point setting allow the economizer to operate at as high of OSAT as possible? Do the dampers fully open and close when they say they are?	Use EMS to change the changeover setpoint or overwrite the OSAT to cause economizer to modulate, etc. Calibrate and check issues in the Analysis Summary.
Supply air temperature (SAT) and reset	Supply air temperature, reset parameter (OSAT, zone demand, etc.) *(2 min.)*	Graph SAT against OSAT or zone demand and compare to reset schedule, or analyze columnar data, similarly. See general idea in Figures 3 and 4.	Use the EMS to change the load to cause the reset-calling parameter to change. Observe setpoint and temperature change appropriately.
VAV duct static pressure control	Duct static pressure (and reset parameters if its reset) *(2 min.)*	Observe that for fixed static pressure systems, that the pressure remains the same during the monitoring period; and for reset systems, that the static pressure follows the reset schedule.	Use the EMS to change the H/C load and cause a change in the pressure control parameter. Analyze per adjacent cell.

Table 1. Sample Trends and Functional Spot Tests (3 pages)

Issue or Equipment	Points to Trend and *Sampling Interval*	Analysis Summary	Functional Spot Tests
Equipment interfaces with the EMS (rooftop units, boilers, fire, safety, etc.)	Setpoints, control loops, point values *(varies)*	Verify which system (EMS or packaged unit) has control of the components to make setpoint changes, control strategies, etc. Calibrate EMS and packaged sensors used for sensing the same point.	Run the system through the sequences of operation in various modes. Change setpoints and observe proper reactions.
Short cycling (DX compressors, condensers, boilers, cooling tower fans)	COV for on / off issues (*COV or value stream at 2 min.*)	View columnar data for analysis of COV. For time series, observe the frequency and magnitude of change.	Use trend log instead.
Hunting (SAT, fan static pressure, cooling and heating coil valve, inlet guide vanes, etc.)	Actuator position or command or COV *(2 min.)*	Plot against time and observe hunting. See Figure 1.	Use trend log instead.
Terminal unit	Zone temperature, heating coil valve position and command, air cfm or damper position, cfm set point, OSAT and duct static pressure*(2 min.)*	Plot with two Y-axes for resolution (valve position on right axis). Observe that the zone temperature remains within 1F of the dead band range, that the cfm is not over or undershooting its setpoint or hunting, that the heating valve is not hunting and that the cfm is at minimum before the heating valve opens, etc.	Use the EMS to change the H/C load or call. Observe that the TU sequences are met. Use a trend log also.
Staging (DX compressors, chillers, cooling towers, boilers)	Stage, controlling parameter, OSAT, RAT, SAT (DX stage is rarely an EMS point. Consider dataloggers.) *(2 min.)*	Observe that the stages are not short cycling, that the minimum ON/OFF times are not violated, and that the staging is reasonable relative to the causal conditions (OSAT and RAT).	Use trend log instead.
Face and bypass dampers	Heating and cooling coil valve position, return air temp., SAT, OSAT, cooling and heating coil air temp., damper position, chilled water supply temperature *(2 min.)*	Observe that SAT setpoint is maintained, that CCV is shut when HCV is open, that there is a deadband when both are closed, that design temperature differences are met, that CC air temp. is equal to the HCT air when CCV is shut, (else CCV leak-by), that SAT equals CCT plus fan dT when dampers are full face (else damper leak-by), etc. See Figure 6.	Use the EMS to change the heating or cooling load or call. Observe that the dampers and valves sequence appropriately, per the adjacent analysis cell. Use a trend log also.
Building demand	Building kW *(15 min. pulse meter)*	Look for demand spikes during startup. Examine and justify unoccupied period energy use level and starting and stopping times. See Figure 7.	Use trend log or monitor instead.
Lighting schedules and sweep controls	Lighting panel ON / OFF *(COV or 15 min. value stream)*	Observe that lighting panels are ON and OFF per desired schedule.	Change schedule to sweep or shut OFF lights now. Observe results. Verify all lights in all parts of the building.
Exterior lighting photocell	Lighting circuit ON / OFF status, photo cell output *(COV)*	Verify that lights go ON and OFF according to the design sequences	Manually verify that lights go ON and OFF appropriately and that sensor is calibrated.

Table Abbreviations: OSAT outside air temperature. WB wet bulb. CHWST chilled water supply temperature. CHWRT chilled water return temperature. PF power factor. V volts. A amps. W watts. EMS energy management system. VSD variable speed drive. MAT mixed air temperature. RAT return air temperature. SAT supply air temperature. H/C heating or cooling. DX direct expansion. CCV cooling coil valve. HCV heating coil valve. dT temperature differential.

CONCLUSION

Calibrated energy management systems provide a valuable tool for assessing the operating functions of HVAC and lighting components in buildings. The method of monitoring actual system operation over time using trend logs can be used to identify complex and often subtle malfunctions. Likewise, functional spot testing that relies on calibrated control signals and immediate observation of system response provides another method for diagnosing and troubleshooting component and system performance.

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